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Review of Reverberant Sound Power Measurement Standard and Recommendations for Further Research

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Preface

Determination of the sound power emitted by small sources using reverberation rooms is becoming increasingly important as society seeks to implement noise control measures. Many of the critical measurement processes are indicated in American National Standard S1.21-1972, "Methods for the Determination of Sound Power Levels of Small Sources in Reverberation Rooms". This standard, as now embodied, represents a major advance in the state-of-the-art of reverberation room measurement of sound power. It incorporates the best currently available interpretation of measurement technology which is the subject of ongoing research.

In order to identify additional analytical and experimental information needed for further refinement of this important standard, this report was prepared under contract with the Applied Acoustics Section of the Mechanics Division, Institute for Basic Standards, National Bureau of Standards, by D. Lubman & Associates.

The opinions expressed in this report are those of the contractor and do not represent an official position by the National Bureau of Standards. The report is made available in the interests of an open exchange of information and in the belief that it is a relevant commentary on the current state-of-the-art.

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Abstract

This report presents a critical review of American National Standard S1.21-1972, "Methods for the Determination of Sound Power Levels of Small Sources in Reverberation Rooms". This standard, as now embodied, represents a major advance in the state-of-the-art of reverberation room measurement of sound power. This report was prepared in order to identify additional analytical and experimental information needed for further refinement of this standard. The report presents a detailed critique of specific items in the standard. Indications are given of both general research areas for statistical room acoustics and of specific research areas for improved reverberant room sound power measurements.

Key words: Acoustics, noise, reverberation room, sound power, statistical room acoustics.

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Review of Reverberant Sound Power Measurement Standard
and Recommendations for Further Research

1. Introduction

Most knowledgeable people would agree that American National Standard Methods for the Determination of Sound Power Levels of Small Sources in Reverberation Rooms, S1.21-1972[1][1/] is a state-of-the-art standard representing a major improvement in sophistication for measurements of this type. This 24-page document supersedes the 5-1/2 pages devoted to the subject in its predecessor, American National Standard S1.2-1962. The new standard permits, for the first time, reverberation measurements of pure tone sound power -- an advance of considerable practical importance. Also, for the first time an attempt is made to estimate total measurement precision.

From a theoretical viewpoint, much of what is "new" in the new standard may be called "statistical room acoustics." The theory of statistical room acoustics, though only partially completed, has already emerged as a powerful tool for both theoretical and applied room acoustics. Its importance to the future of this field would be hard to overemphasize in view of historical perspective.

Wallace Clement Sabine, often called the father of modern room acoustics, recognized the essential statistical nature of his subject. Despite his many remarkable and lasting contributions, Sabine was unable to work out fully this approach. As F. V. Hunt remarks in the introduction to Sabine's Collected Papers on Acoustics[2], "This technique represents one of Sabine's efforts to put the distribution of sound, like reverberation, on a firm quantitative basis. Unfortunately, this goal eluded him as it has continued to elude all who have followed him."

The next great contribution to our understanding of room acoustics was made in the 1930's and early 1940's by such men as Morse, Bolt, and Maa,[3,4] who developed the normal mode approach. The problem of room acoustics was basically viewed as a boundary value problem against which the powerful techniques of partial differential equations could be brought to bear. This approach proves most useful at low frequencies. However, as frequency increases, this formalism rapidly loses its usefulness as a means for determining the distribution of sound in rooms. The enormous number of room modes, the sensitivity of the complicated boundary value problems to subtle variations of room geometry and surface impedance, and the numerical difficulties engendered by irregular geometries are each great barriers which limit the practical utility of this approach at high frequencies.

Statistical room acoustics -- the most recent great advance -- was begun by the German school, notably by Schroeder[5], starting in the mid 1950's. Statistical room acoustics is most useful at high frequencies (more precisely, at high modal overlap), just where the modal approach becomes intractable. The triumphs of the new approach have already had significant impact in this field. In particular, the goal of putting the distribution of sound on a firm quantitative basis (F. V. Hunt's lament) has already been substantially realized. The measurement of pure tone reverberant sound power is a specific example of the application of statistical room acoustics to practical needs.

Another example is the recently proven effectiveness of the rotating diffuser. The first use of moving vane diffusers may be traced back to Sabine. But despite numerous attempts to prove their usefulness, the American acoustics community as a whole remained, at best, marginally convinced, and moving vanes never did come into fashion in Europe. Statistical room acoustics has changed all this. With the development and proof of a theory to predict spatial fluctuations of sound in reverberation rooms, it took but a few simple experiments to prove the great effectiveness of rotating diffusers over their staionary counterparts. Statistical theory even provides a measure of their effectiveness, known as the "figure of merit."

1/ Figures in brackets refer to literature references at the end of this report.

Still another example is shown by the recent advances in quantifying the benefits of continuous spatial averaging. This modern application of statistical room acoustics has intellectual heritage in the work of Cook, Waterhouse, et al.[6], who defined spatial correlation functions for diffuse reverberant sound fields. This work has proven valuable in estimating one important component of the total uncertainty in reverberant sound power determinations.

Another important obstacle to overcome before limits could be placed on total measurement uncertainty was the variation of sound power output with source position. Great progress toward this end was made by Lyon[7], using statistical room acoustics.

The subject standard has incorporated these and other results of statistical room acoustics. That is one of its strengths. Conversely, many of the weaknesses of the current standard are traceable to our present incomplete understanding of statistical room acoustics, or to their incomplete incorporation. It would seem, then, that many future improvements to this standard are tied to continued development of this approach. For this reason, some general areas where theoretical research into statistical room acoustics seems needed are briefly described in Section 3.

2. Critique of Specific Items in Subject Standard

2.1. Discussion of Direct Versus Comparison Method

This standard does not give ample recognition to the fact that estimates of total measurement uncertainty are somewhat different for direct and comparison methods. The comparison method contains two additional sources of error. One is due to the uncertainty in determining the power output of the reference source (which is sensitive to position at low frequencies). This error source is mentioned in Ref. 2 of the standard, but does not seem to have been included in the assessment of total measurement uncertainty. The other source of error is due to estimating the mean squared pressure for the reference source; i.e., there are two errors in estimating mean squared pressure: one for the unknown and one for the reference source. To illustrate that this is indeed a problem, we will sketch a derivation of the total measurement variance for the comparison method when only one source position is used ($N_s = 1$) and show it is different from Maling's expression given in Ref. 1 of the standard.

Computation of sound power of an unknown source in a reverberation room by means of the comparison method makes use of the ideal expression

$$W_x = \frac{\langle p_x^2 \rangle}{\langle p_r^2 \rangle} W_r \qquad (1)$$

where,

W_x = sound power of the unknown source as installed,

W_r = room averaged sound power of the reference source,

$\langle p_x^2 \rangle$ = true room averaged squared pressure of unknown,

$\langle p_r^2 \rangle$ = true room averaged p^2 of the reference source.

Since we do not know the two true room averaged squared pressures in practice, the unbiased estimated $\overline{p_x^2}$ and $\overline{p_r^2}$ are employed. These estimates contain random errors since they are based upon limited sampling. Similarly, the power output of the reference source at any one particular location in the room may be different from the room average power. Its actual power output is designated as $\overline{W}_r$. The estimated power of the unknown source is

$$\overline{W}_x = \frac{\overline{p_x^2}}{\overline{p_r^2}} \overline{W}_r \qquad (2)$$

Clearly, the estimated power $\overline{W}_x$ may be different from the true power W_x because of these three error sources. To estimate the total error, three normalized errors are now defined as follows

$$\overline{p_x^2} = \langle p_x^2 \rangle (1 + \varepsilon_x) \qquad (3a)$$

$$\overline{p_r^2} = \langle p_r^2 \rangle (1 + \varepsilon_r) \qquad (3b)$$

$$\overline{W}_r = W_r \ (1 + \varepsilon_w). \qquad (3c)$$

Using these definitions, one can show that the normalized error in the estimated sound power is

$$w = \frac{\overline{W}_x - W_x}{W_x} = \frac{\varepsilon_x + \varepsilon_w - \varepsilon_r + \varepsilon_x \varepsilon_w}{1 + \varepsilon_r}. \qquad (4)$$

The three epsilons are now treated as random variables having zero mean values. It is further postulated that these three random variables are uncorrelated. In particular, it is assumed

$$E[\varepsilon_x \cdot \varepsilon_w] = E[\varepsilon_x] \cdot E[\varepsilon_w] = 0, \qquad (5)$$

where, E[•] designates mathematical "expectation" (ensemble average). Under these conditions the normalized sound power estimate is unbiased, i.e.,

$$E[w] = 0 . \qquad (6)$$

Because of the zero mean of w, the variance of the normalized sound power estimate is simply

$$\mathrm{Var}(w) = E[w^2]. \qquad (7)$$

Now the problem is to find this variance. This is in general a difficult problem because of the random variable in the denominator of w. In principle, the problem can be solved by assuming probability distribution functions for each of the random variables. Instead a short cut is employed which is valid when the epsilons are smaller than unity, which is usually the case (see Appendix A). This permits use of the binomial expansion

$$(1 + \varepsilon_r)^{-2} = 1 - 2\varepsilon_r + 3\varepsilon_r^2 - 4\varepsilon_r^3 + \ldots \ \varepsilon_r^2 < 1. \qquad (8)$$

Upon squaring eq. 4, substituting the expression above for its denominator, taking expected values as shown by eq. 7, and rearranging terms, it is found that

$$\mathrm{Var}(w) = (\sigma_x^2 + \sigma_w^2 + \sigma_x^2 \sigma_w^2) \cdot (1 + 3\sigma_r^3) + \sigma_r^2$$
$$-2E(\varepsilon_r^3) + 3E(\varepsilon_r^4) + \text{higher terms}. \qquad (9)$$

where,

$$\sigma_x^2 = \mathrm{Var}(\varepsilon_x) \qquad (10a)$$

$$\sigma_w^2 = \mathrm{Var}(\varepsilon_w) \qquad (10b)$$

$$\sigma_r^2 = \mathrm{Var}(\varepsilon_r) \qquad (10c)$$

This result is valid when the epsilons are smaller than unity. When they are much smaller, it is believed that higher moments (from the third on) become negligible and may be ignored. Indeed, when all variance terms are small, the total variance is given by

$$\mathrm{Var}(w) = \sigma_x^2 + \sigma_w^2 + \sigma_r^2 \qquad (11)$$

which is not only an intuitively satisfying result, but is in exact agreement with eq. (2) of Ref. 2 of the standard (Baade). Compare the result of eq. (9) above with that of Maling (Ref. 1 of standard) below:

$$\mathrm{Var}(w) = \sigma_t^2 = \sigma_x^2 + \sigma_w^2 \ .$$

Evidently, the calculation of total measurement variance is more complex than the subject standard assumes. The differences between Maling's treatment and this one can be substantial when the variance is large. The present approach would have to be developed further to take into account multiple source positions. Also, the addition of variances assumed here is open to question at low frequencies, as discussed in the following section.

2.2. Addition of Variances (Sec. 12.1)

In Section 12.1 of the standard it is explicitly assumed that variances of squared pressure (σ_p^2) and source power (σ_w^2) add. The citation to this is Ref. 1 (Maling), which employs the equation

$$\sigma_t^2 = (1/N_s)(\sigma_w^2 + \sigma_p^2) \ .$$

This equation, which may be traced to Andres[15], forms the basis for calculation of the total measurement variance and is embodied, for example, in eq. 7 of the standard. However, it is not a good assumption at low frequencies. In a paper by Ebbing and Maling[8], figure 13 shows that mean squared pressure and source power output are strongly correlated in the 100 Hz band. Therefore, it would seem more appropriate to add the standard deviations rather than the variances at low frequencies. This would result in higher reported measurement variances. To put the matter another way, the equation above may be underestimating total measurement variance at low frequencies.

Examination of figure 12 of the paper by Ebbing and Maling shows that at 500 Hz, the correlation appears to be small. More information is needed on the relationship between these random variables as a function of frequency in order to arrive at more reliable estimates of total measurement uncertainty. (It has already been shown that the equation above seems inadequate to describe errors for the comparison method).

2.3. Measurement Uncertainty (Sec. 1.3)

Justification for the standard deviations of table 1 are not completely clear, satisfactory, or complete. Some of the numbers of table 1 appear to disagree with those in the two references cited here (Refs. 1 and 2 of the standard). A clearer and more thorough explanation seems in order.

2.4. Microphone Positions (Sec. 6.2)

In this section, requirements are set for spatial averaging with sources emitting broad band noise. These requirements, while sounding reasonable, are not explicitly justified or explained either here or in the references. As an alternative to a 3-microphone array, a microphone traversing a 3-metre (minimum) path is offered. At 100 Hz, continuous averaging on a 3-metre path is less effective than a 3-microphone array. Furthermore, the effectiveness is somewhat sensitive to path shape. A linear path at that frequency is equivalent to $N_{eq} = 2.27$ independent samples. A circular path is even less effective, providing an $N_{eq} = 1.61$ independent samples. Therefore, the continuous path of 3 metres is less effective than the 3-microphone array at low frequencies. On the other hand, the path is more effective than the array at high frequencies. The phrase permitting a traverse on "some other geometric figure" is open to possible abuse, since many imaginable geometric figures 3 metres in length are even less effective for averaging than the straight line segment or circle. There seems no reason why guidance cannot be given for the choice of appropriate path shapes.

2.5. Repetition Rate (Sec. 6.2.1)

The requirement for completion of a whole number of microphone traverses or array scans is interesting. Use of this procedure will provide greater repeatability, but will suppress genuine variability due to incomplete spatial averaging -- a variability which is counted in the table of measurement uncertainties (table 1). Thus, it could conceivably give false confidence to experimenters at times. One wonders if this procedure should be made a recommendation rather than a requirement. Since an integration time of 30 seconds is recommended, it would be convenient to have a turntable whose period is 30 seconds. The only available commercial turntable (Brüel & Kjaer Type 3921) has a period of 80 sec. Perhaps the manufacturer could be persuaded to provide accessory gears to obtain different periods.

2.6. Location of Microphone Traverse or Array (Sec. 6.2.2)

The formula given here for minimum distance between the sound source and the nearest microphone position produces a direct field bias of 3 dB. (This is for the far field of a source having a directivity factor of 2 such as obtained for a monopole above a reflecting plane). A bias of 3 dB hardly justifies the statement that "the contribution of the direct field to the measured mean squared pressure is negligible". The minimum distance will ordinarily be set at the highest frequency where T_{60} is least. One wonders if a correction for direct field bias in the sound power determination would be appropriate. The presence of a substantial direct field will undoubtedly cause substantial changes in the apparent spatial variances and this could result in difficulties in qualifying the room at higher frequencies. A direct field bias would occur if the microphone positions are at various distances from the source. Conversely, the apparent spatial variance will be lower due to direct field bias if the microphone positions are all at about the same distance from the source. This could result in qualification of a room which should not be qualified.

The requirement that "the microphone traverse or array shall not lie in any plane within 10 degrees of a room surface" seems spurious if the microphones are out of the interference patterns of room walls. We must remember that the implicit assumption is that the sound field is random in regions remote from room boundaries, so that one plane of traverse is (a priori) as good as any other.

2.7. Determination of the Significance of Discrete Frequency Components and Narrow Bands of Noise (Sec. 6.3)

One wonders concerning the basis for choosing n = 6 samples for estimating sample standard deviations in eq. 1. There are two types of risk which should be assessed. First, what is the probability of finding $s \leq 3$ given that a pure tone is present? The risk of this occurrence may be substantial when n is so small. The consequence of this innocent error would be serious since a pure tone component could then be measured using the relaxed technique appropriate for noise. There is also a risk of falsely concluding that a pure tone is present when in fact it is not. For this discussion, let σ designate the population standard deviation of which s is an estimate based on 6 samples. The probability of finding $s > 3$ given both $\sigma \leq 1.5$ and $1.5 \leq \sigma \leq 3$ should be calculated. These probabilities represent the risk of having to follow a measurement procedure more elaborate than is actually necessary. If these risks are judged too high, perhaps an alternate procedure can be suggested, using $n > 6$ for example. In order to compute these risks reliably, the probability distributions should be known. While this seems well in hand for frequencies corresponding to high modal overlap (high frequencies), problems can be anticipated at lower frequencies where the probability distributions are less well understood and perhaps even less reliable.

Equation 1 employs estimated standard deviations of sound pressure level instead of squared pressure. While this is more convenient, it may be less reliable, especially for pure tones. The "theoretical" standard deviation of level for a pure tone of 5.57 dB is rarely found in practice, smaller values being more common. For some reason -- perhaps limited signal-to-noise ratio -- this commonly found discrepancy has not received the attention it deserves. The standard deviation of level is far more sensitive to limited signal-to-noise ratio (S/N) than is the standard deviation of squared pressure. Even an average S/N of 10 or 20 dB may significantly suppress measured values of standard deviation of level for a pure tone, while having little effect on the standard deviation of p^2. Some years ago, the probability distribution of sound pressure level in a purely reverberant field was derived based upon an assumed Chi-square distribution of p^2[A.2]. This work also gave the standard deviation of sound pressure level for both pure tones and for noise. (Schroeder's figure of 5.57 dB was verified here.) This work can be extended to account for limited S/N.

At low frequencies, where the modal overlap is low, the probability distributions of p^2 deviate from the ideal Chi-square. It will be possible to find the probability distributions and variances of level for excitation of isolated axial, tangential, and oblique modes. This may provide valuable insight into what should be expected from the procedure of 6.3.3 in rooms at low frequencies.

2.8. Alternate Qualification Procedure for the Measurement of Discrete-Frequency Components (Sec. 13)

It was the intent of this section to provide a set of "statistically independent frequency response measurements" in each 1/3-octave band. For this purpose table 7 lists a set of test frequencies (or periods) together with tolerances for increments. For the purpose of guaranteeing reliable assessments of variance, it is sufficient that responses at the various frequencies be uncorrelated (statistical independence is too strong a requirement). Because of the nature of rooms, the responses are never completely uncorrelated, though the correlation becomes exceedingly small when the frequency interval Δf becomes large. Schroeder[5] provides a "frequency autocorrelation function" for response of a reverberation room. It can be expressed as

$$\rho(\Delta f) = [1 + (\Delta f\ T_{60}/2.2)^2]^{-1} \qquad (12)$$

where Δf is the frequency increment. For practical purposes it can be assumed that room responses are essentially uncorrelated when $\rho(\Delta f) \leq 0.1$. This implies a minimum value of reverberation time for a given frequency increment Δf: for essentially uncorrelated room responses

$$T_{60} \geq 6.6/\Delta f. \qquad (13)$$

If the reverberation time is much less than given above, the room responses are highly correlated over the frequency increment. Unfortunately, this can actually happen when the increments of table 7 are used. For example, at the low end of the 100 Hz band the nominal frequency increment is 0.819 Hz. This prescribes a minimum reverberation time of 6.6/0.819 = 8.06 seconds in the 100 Hz band. It is evident that the reverberation time will often be lower than this, particularly in small rooms and especially in those rooms treated with increased low frequency absorption. Therefore, the standard deviations computed from eq. 8 of the standard will sometimes employ highly correlated samples, a violation of the intent of the standard.

When one considers the wide tolerance increments for frequencies, the situation becomes even worse. For example, using worst case tolerances for the lower end of the 100 Hz band gives Δf = 0.3276 Hz and a minimum reverberation time of 20.1 seconds -- clearly unacceptable. A table of minimum reverberation values (for worst case frequency tolerances) based on table 7 of the standard is given below.

THIRD-OCTAVE BAND CENTER FREQUENCY Hz	T_{60} (Low End) sec	T_{60} (Mid Band) sec	T_{60} (High End) sec
100	20.15		13.51
125	25.79		4.26
160	16.40		10.61
200	20.51		13.51
250	6.56		4.23
315	8.20		5.30
400	4.99		3.46
500		3.22	
630		3.30	
800		3.30	
1000		1.65	
1250		1.65	
1600		1.32	
2000		0.66	
2500		0.66	

2.9. Calibration of Reference Sound Source (Sec. 10.2)

Calibration accuracy for the reference sound source required by table 3 of Sec. 10.2 is higher than claimed by the subject standard in table 1. The questions is: how does one calibrate the reference source to this higher accuracy in a reverberation room?

An Appendix to the subject standard needs to be developed which prescribes a procedure for reference source calibration. It should specify the number of source and microphone locations. A correction procedure for removing direct field bias may also be necessary.

2.10. Loudspeaker Tests (Sec. 13.4)

As part of the justification for the loudspeaker test, Ebbing and Maling[8] provide arguments to show that near field level fluctuations over frequency are proportional to changes in source power level for frequencies such that $ka < 1$. These arguments are based upon estimates of the normalized specific radiation impedance of the source for three different baffle conditions. However, it did not specifically take into account the possible near field (Fresnel) fluctuations due to small source-microphone separations recommended in the standard. In order to verify that such near field effects can be ignored, an equation was derived giving the ratio of near field intensity to the average far field intensity (which is proportional to radiated power). The model, chosen for tractability and pertinence, is a baffled rigid circular piston radiator. The microphone was assumed to be on the piston axis, 2 cm from the surface. Calculated results are presented in figure 1. Results strongly support the loudspeaker test procedure. They show the proportionality existing between near field levels and far field radiated power is maintained well up to $ka \simeq 1$. The equation derived for these calculations is

$$I_{nf}/I_{av} = \frac{16\pi r^2 \sin^2\left[\frac{k}{2}\left(\sqrt{r^2 + a^2} - r\right)\right]}{a^2\left[1 - \frac{2J_1(2ka)}{2ka}\right]} \tag{14}$$

where,

I_{nf} = nearfield intensity measured at r.
I_{av} = average intensity in far field (proportional to radiated power).
r = distance from microphone to piston surface.
k = wave number in air ($2\pi f/c$).
a = radius of circular piston.
f = frequency in Hz.
c = velocity of sound in air.
J_1 = first order cylindrical Bessel function.

Another question that was satisfactorily answered here pertains to the ratio of nearfield squared pressure to average reverberant squared pressure -- which is a kind of signal-to-noise ratio against which room qualification measurements must be made. This ratio must be large enough to ensure that nearfield room levels are not contaminated by reverberant levels under any practical room conditions.

The baffled circular piston model was used again, with measurement distance of 2 cm as before. The exact result derived is

$$I_{nf}/I_{rev} = \frac{8A}{a^2} \cdot \frac{\sin^2\left[\frac{k}{2}\left(\sqrt{r^2 + a^2} - r\right)\right]}{\left[1 - \frac{2J_1(2ka)}{2ka}\right]} \tag{15}$$

where,

I_{nf} = nearfield intensity at r.

I_{rev} = average reverberant field intensity.

A = total absorption in room (L^2).

For example, in a cubical room of 200 m^3, $S \simeq 205\ m^2$. For an absorption coefficient of 0.01, $A = 2.05$. Let the piston radius be $a = 0.0508$ m. Then $8A/a^2 = 6.36 \times 10^3$. At

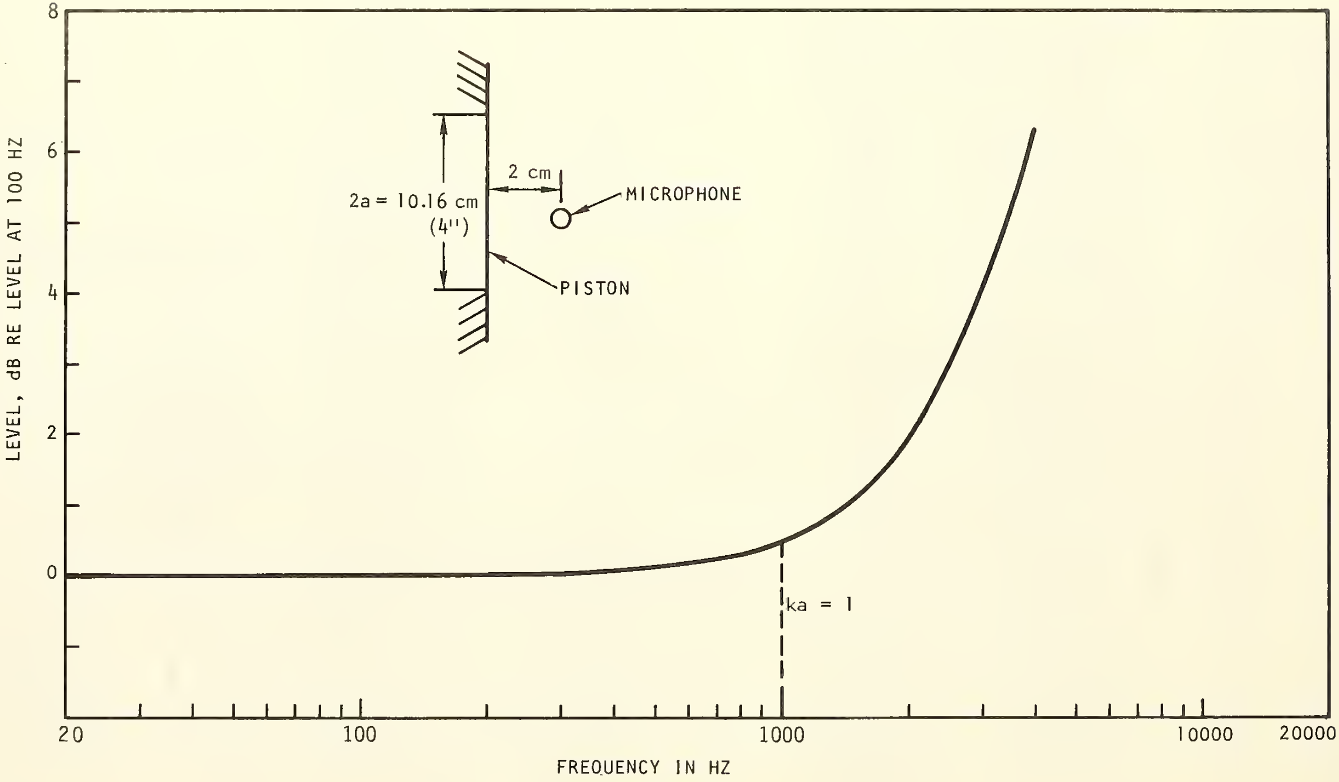

Figure 1. Ratio of nearfield intensity to average farfield intensity. Levels are re: level at 100 Hz for a microphone located 2 cm from the plane of a baffled circular piston radiator, on axis.

1000 Hz, r = 0.02 m. then,

$$I_{nf}/I_{rev} = 1.64 \times 10^3, \text{ or } 32.2 \text{ dB}. \qquad (16)$$

3. General Research Areas for Statistical Room Acoustics

3.1. Transition Between Classical Modal Theory and New Statistical Theory

Many current problems could be solved if the transition between classical modal theory at low frequencies and the new statistical theory at high frequencies was better understood. The transition frequency is given roughly by the Schroeder frequency (3:1 modal overlap). The index of modal overlap at any frequency, f, is defined as the ratio of average modal bandwidth to the average frequency spacing between modes. It may be viewed as the expected number of modes excited by a pure tone source located in a corner of the room. A formula for the Schroeder frequency, f_c, giving a modal overlap index of 3 in an air-filled room at normal temperature is

$$f_c = 2 \times 10^3 \, (T_{60}/V)^{1/2} \qquad (17)$$

where T_{60} is the reverberation time in seconds and V is the room volume in cubic metres.

Practical measurements are now made down to frequencies somewhat below the Schroeder frequency. Measurement uncertainties are largest here, and also hardest to predict. The explanation is that since few modes are excited statistical predictions of the variances of sound power and squared pressure are less reliable than at high frequencies.

Also, with few modes excited, statistics are sensitive to the type of mode excited and the degree of excitation (influenced by source location and source frequency relative to mode frequency). As frequency is increased, the number of modes becomes so great that statistical prediction becomes highly reliable.

Modal theory and statistical theory should be unified so that the orderly transition between them is understood. As a first step toward that goal, it would seem useful to continue the careful examination of statistics for excitation of few modes. Among the practical problems which could be illuminated by this study are the suppression of source power output at low frequencies, and the question of optimum room absorption at low frequencies, both of which are discussed under separate headings.

Another problem is the correlation of errors at low frequencies. The variances of sound pressure squared and of source power are assumed in the subject standard to be uncorrelated. However, there is evidence that they are correlated at low frequencies. This, too, is discussed under a separate heading. Also, the variance of power output with source position - the dominant error term at low frequencies - needs more attention. Only the cases of infinitesimal monopole and dipole sources have been examined so far. The variances for practical (e.g., spatially extended) sources needs to be examined as well. Finally, the hypothesis of "mode splitting," which has been offered to account for measured variances lower than theoretically predicted, has not yet been satisfactorily verified. It is fairly sizable, amounting to as much as a factor of 1/2 in variance at lowest frequencies.

3.2. Further Development of Statistical Theory at High Frequency

Statistical room acoustics also needs further development at high frequencies. Some key areas deserving of serious attention are briefly mentioned.

The Schroeder theory for frequency response fluctuations has not been adequately verified experimentally. Direct verification seems overdue, since this theory is central to the determination of spatial variance for frequency averaging. Schroeder's work was done mainly using Monte-Carlo simulation rather than by direct measurement. In particular, it would be useful to test experimentally Schroeder's "frequency autocorrelation function" in order to validate it, and to get some idea of its practical limitations. For example, variations of room absorption over small frequency intervals could be important in explaining discrepancies in measured spatial variance which have sometimes been noted.

The present theory for continuous spatial averaging is limited to discrete frequencies or extremely narrow bands of noise. It should be extended to allow for simultaneous space and frequency averaging, which is the case most often found in practice.

There appears to be a contradiction between theory and measurement on the time averaging requirements for noise signals. The irregular frequency response of reverberation rooms leads to theoretical predictions of higher variance than has been reported in the one study contained in the literature [10].

3.3. Theory for Room Qualification

In order to lay claim to understanding the basis for the new standard, it should be possible to predict from theory the results of the qualification procedure of Section 13 for ideal rooms. The goal should be to predict the standard deviation of eq. 8 and the parent probability distribution. This is admittedly an ambitious undertaking, but the necessary elements seem to be available. There is a theory for the fluctuations of squared pressure versus frequency which seems valid at high modal overlap. There is also a theory which transforms the statistics of squared pressure into statistics of sound pressure level. Further theories accounting for the effects of spatial averaging, and predicting sound power fluctuations with source position exist. It may be possible to combine these to get theoretical estimates for the standard deviation of eq 8. Efforts to obtain such a theory which has good agreement with the now proliferating measurements from laboratories around the world will be most helpful in pointing out the weak spots to an understanding of these phenomena. It would certainly produce further directions for future research.

4. Specific Research Areas for Improved Reverberant Sound Power Measurements

4.1. Rotating Diffusers

One of the most urgent and fruitful areas for applied research would seem to be the rotating diffuser. The rotating diffuser is the most effective device known for improving the precision of reverberant sound power measurements. One of its main benefits is the reduction of pressure variance in reverberation rooms. The consequence is a dramatic reduction in the number of microphone systems (or path length for a moving microphone) necessary for room qualification and measurements. The figure of merit M' is a direct measure of this benefit. Though figures of merit between 2 and 4 seem typical, values over 10 have been reported. This shows that improved design may provide greatly improved performance. At present, no viable theory for the rotating diffuser exists and there is no solid basis for providing design recommendations.

Another potentially important, though less well-documented, benefit is the reduction of sound power variance, the dominant error term at low frequencies. This will reduce the number of source positions necessary for qualification and measurements - an important consideration for all measurements and a crucial one for measurements on large equipment or sources which are not easily moved. It is possible to define and measure corresponding figures of merit for reduction of source power variance.

A third benefit is the improvement of diffuseness, with consequent improvement of the accuracy of all reverberation measurements.

In view of the complexities, it is believed that a fully rigorous theory explaining rotating diffuser performance is not within sight. Instead, an heuristic, or semi-empirical theory seems a much more promising approach for payoff over the next few years.

The main goals for rotating diffuser research are suggested below.

First, model studies of various rotating diffuser configurations leading to short term recommendations of effective shapes. Second, systematic experimental determinations of the relationship between performance, design, and room parameters. Major design parameters are thought to include size, shape, percent open area, and speed. Major room parameters are room size and reverberation time. Third, development of a semi-empirical theory to explain rotating diffuser performance and then to predict rotating diffuser performance from design parameters. The experimental and theoretical studies should run concurrently.

Studies of the benefits of the rotating diffuser for improving diffuseness are hampered by the lack of instruments for measuring diffuseness. This subject is discussed under a separate heading.

4.2. Measurement Diffusion

Central to all reverberation room measurements is the need for a diffuse field. In practice, reverberant fields are often far from diffuse. Indeed, the very definition of diffusion seems unsatisfactory to many thoughtful workers, partly because the tools for its measurement are lacking. The practical consequences of employing imperfectly diffuse fields are legion. Among them are reduced accuracy and precision of sound power measurements, and substantial discrepancies in the measurement of sound absorption coefficients and transmission loss.

Some practical means for assessing the degree of directional diffusion in rooms is needed. Recently, two suggestions have been advanced toward that end. One[11], called "paraholography" is said to provide a means for decomposing a practical sound field into constituent plane waves. In principle, it can provide the number of plane waves, their amplitudes, phases, and directions of propagation. Another suggestion[12], called "traversing microphone spectroscopy," provides a frequency domain representation of the spatial correlation function, which is intimately connected with diffusion. These two suggestions seem worthy of further examination with a view toward development of a practical diffusion meter.

4.3. Suppression of Sound Power Output at Low Frequencies in a Reverberation Room

As frequency is reduced below the Schroeder frequency in a reverberation room the measured sound power output of a source seems to become systematically lower than that measured in a free field. An example of this phenomenon may be seen in figure 8 of Schultz[13]. Discrepancies of 5 dB or more are possible. For this reason, reverberant sound power measurements may be dangerously misleading at low frequencies when results are applied to non-reverberant rooms, or to rooms of different size. Also, discrepancies between laboratories measuring the same source may be anticipated at low frequency.

This phenomenon has not received the attention it deserves. An attempt to deal with it in the subject standard led to the inclusion of a correction term $(1 + S\lambda/8V)$ which serves to increase reported sound power at low frequencies. Justification for use of this term is provided by the claim of sound energy density buildup near room boundaries. The term contributes about 1.3 dB at 125 Hz in a 200 m^3 room. This is not enough to account for observed discrepancies. Some members of the working group who prepared this standard believed that the term should be employed twice (i.e., 2.6 dB at 125 Hz) but could not obtain a consensus.

Without passing on the merits of the energy density arguments, another explanation for this phenomenon may be offered. As frequency is lowered, the index of modal overlap becomes small. A broad band source should couple less energy into a room at frequencies where modes are sparse. Consequently, its band averaged power output should be lower than in a free field. If this explanation is correct, discrepancies between reverberant and free field power measurements will depend upon modal overlap, and would become systematically smaller as low frequency absorption is increased. In contrast, the correction term $(1 + S\lambda/8v)$ is independent of absorption.

It is suggested that an experimental test of this hypothesis be made. It should be noted that these two explanations are not mutually exclusive, and must be examined separately.

4.4 Sound Energy Density

The time averaged sound energy density at a point, E, and its room-averaged value, $\langle E \rangle$, are of fundamental importance in the theory of reverberation room acoustics. The basic differential equation for diffuse field sound power measurements is solved by assuming that in steady state, E is uniform throughout the room. The resulting expression for sound power W is

$$W = EAc/4 \tag{18}$$

where A is the room absorption and c is the speed of sound.

In practice, energy density is not measured. Instead the mean squared sound pressure is averaged over space to provide an estimate of $\langle p^2 \rangle$, and the relation $E = \langle p^2 \rangle / 4\rho c^2$ is employed, where ρ is the density of the medium.

It is unfortunate that we have no energy density meter in acoustics. Such an instrument would be useful in at least three ways.

First, it could answer serious questions about the validity of fundamental equations used for sound power measurments. In particular, there is controversy over the claim of sound energy density buildup near room boundaries. As mentioned above, a correction term $(1 + S\lambda/8v)$ based on this claim is now included in the formula for sound power contained in the subject standard. This term was not used in its predecessor S1.2-1962. Verification of this claim by direct measurement of E could resolve this controversy.

Second, a practical energy density meter could substantially improve the precision of reverberant sound power measurements. There seems to be general agreement that while E will not be uniform in a reverberation room, its fluctuations over space will be substantially lower than corresponding fluctuations of p^2. The essence of this belief is the p^2 measurements provide only the potential energy component of reverberant E, and that the kinetic energy portion (associated with particle velocities) will "fill in" the spaces in the room where potential energy (and hence, p^2) is low, the result being smaller spatial variations for E than for p^2.

Third, it might prove useful in assessing diffusion in reverberation rooms. At least one textbook definition of diffusion requires uniform energy density.

In view of its practical applications, some effort seems warranted to examine the feasibility of constructing an energy density meter. At the very least, the present obstacles to that end could be delineated.

In addition to the development of an energy density meter, it would seem useful generally to re-examine the question of the distribution of energy density in standing wave fields theoretically. There seems to be genuine confusion over this concept. The confusion extends to textbooks and standard definitions. If energy density does build at room boundaries does this not violate the assumption of uniform E made in solving the differential equation for sound power? Is energy density uniform in a diffuse field?

4.5. Optimum Absorption Versus Frequency Curve

Evidently, there is an optimum curve of absorption versus frequency which minimizes the total random error in reverberant sound power measurements. Doubtless, the optimum curve will show absorption diminishing with increasing frequency. The optimum curve will be most important in the low frequency range within an octave or two of the Schroeder frequency. The optimum curve may not be easy to determine because tradeoffs between pertinent parameters are not yet well understood.

High absorption is desirable at low frequencies because it reduces the variance of sound power with position. This term accounts for most of the random error at low frequency. Rotating diffusers are also expected to reduce this variance. However, it seems likely that high absorption will reduce the effectiveness of rotating diffusers in this respect. The optimum absorption versus frequency curve must balance these tradeoffs. The spatial variance of p^2 also enters into this discussion. This term dominates measurement precision at higher frequencies. At high frequencies the variance of p^2 increases with absorption (for broad band sources). For this reason, absorption should ideally be made small at high frequencies. However, at very low frequencies, experimental results indicate a reversal of this dependence. Increased absorption evidently reduces the variance of p^2 at very low frequencies. The theory for predicting variance of p^2 needs to be extended to account for these effects at low frequencies. Once again, the rotating diffuser must be considered, since the evidence is that high absorption tends to reduce the effectiveness of the rotating diffuser in reducing the variance of p^2.

In summary, the total measurement variance may be minimized by finding an optimum absorption versus frequency curve. To find it, the dependence of two kinds of rotating diffuser figures of merit on absorption and frequency, (i.e., one for reduced spatial variance of squared pressure and one for reduced variance of source power output) must be studied. The present theory for spatial variance must also be extended to frequencies around and below the Schroeder frequency.

4.6. Round Robin for Sound Power Measurements

Since a number of laboratories have qualified[14] under American National Standard S1.21-1972, a round robin for sound power measurements is feasible and is a logical follow-through for this new standard. A round robin also seems desirable in view of the remaining doubts about measurement accuracy, especially at low frequencies.

4.7. A Primer on Reverberation Measurements

In view of the rapid growth in the number of technical people involved in reverberation measurements and of the increasing technical complexity of the subject, there appears to be a growing "knowledge gap." To close this gap, preparation of a primer on reverberation measurements and even a treatise on reverberation room acoustics would seem very useful.

The primer should provide adequate technical background for professionals involved in conducting these measurements, and should be aimed at those whose background includes only a single undergraduate course in acoustics or the equivalent experience. The primer should provide technical background for the measurement standards in understandable terms, and should serve as a technical guide for the design and conduct of measurements. Its contents might include discussion of the fundamental working equations for steady state and transient behavior of rooms; instrumentation and procedures for conducting measurements; the transition between the deterministic view at low frequencies and the statistical view at high frequencies; statistical behavior relating to precision of measurements; statistics for excitation with a pure tone, multitones, and noise; spatial correlation and its pertinence for spatial averaging and diffuseness; practical limitations at low frequencies and recommendations for their improvement; limitations at high frequencies such as air absorption and direct field bias; and rotating diffusers. Guidelines and worked examples of the application of these principles to practical measurement problems should be included throughout, along with references to contemporary literature. Examples of design of and instrumentation for qualified rooms might also be included. Finally, the possible use of this primer as a textbook on reverberation room acoustics should be considered.

4.8. Design Recommendations for Reverberation Rooms

Even in retrospect, the decision to make American National Standard S1.21-1972 a <u>performance</u> standard seems wise. However, with the present rapid growth of knowledge and experience, it should soon become technically feasible to develop design recommendations for rooms which are likely to meet performance standards with minimum effort. The decision to provide design recommendations involves numerous questions of policy and economics. How much of this information should be provided by the government and how much by private consultants? Certainly, the number of new laboratories projected over the next few years would have to be sufficient to provide economic justification.

It seems likely that many new laboratories would prefer to "emulate" successful facilities rather than innovate new designs. Indeed, the availability of detailed design recommendations could favorably influence the decision to construct new facilities because of the reduced cost and risk. The consequent improvement expected in measurement uniformity and comparability between laboratories would be another advantage to be gained.

5. References

[1] American National Standard Methods for the Determination of Sound Power Levels of Small Sources in Reverberation Rooms, S1.21-1972, American National Standards Institute, New York, New York, 1972.

[2] Sabine, W. C., Collected Papers on Acoustics, Dover Publications, Inc., New York, New York, 1964.

[3] Morse, P. M., and Bolt, R. H., "Sound Waves in Rooms", Review of Modern Physics 16, April 1944, pp. 69-150.

[4] Maa, D. Y., "The Distribution of Eigentones in a Rectangular Chamber at Lower Frequency Ranges", J. Acous. Soc. Am. 10, 1939, p. 258.

[5] Schroeder, M., "Die Statistischen Parameter der Frequenzkurven von Grossen Räumen", Acustica 4, 1954, pp. 594-600.

[6] Cook, R. K., Waterhouse, et al, "Measurement of Correlation Coefficients in Reverberant Sound Fields", J. Acous. Soc. Am. 27, 1955, pp. 1072-1077.

[7] Lyon, R. H., "Statistical Analysis of Power Injection and Response in Structures and Rooms", J. Acous. Soc. Am. 42, 1967, pp. 859-865.

[8] Ebbing, C. E., and Maling, G. C., Jr., "Reverberation-room qualification for determination of sound power of sources of discrete-frequency sound", J. Acous. Soc. Am. 54, 1973, pp. 935-949.

[9] Lubman, D., "Spatial Averaging in a Diffuse Sound Field", J. Acous. Soc. Am. 46, 1969, pp. 532-534.

[10] Ingalls, D. J., "Integration Time Variance in Reverberation Room Measurements", J. Acous. Soc. Am. 51, 1972, p. 1825.

[11] Cook, R. K., "Paraholography - A New Method for Measurement of the Directional Distribution of Sound Waves in a Reverberation Chamber", presented at the 86th Meeting of the Acoustical Society of America, Los Angeles, California, October 1973. (Abstract published in the J. Acous. Soc. Am. 55, 1974, p. 431.)

[12] Lubman, D., "TM Spectra: A Measure of Diffuseness of Reverberant Sound?", presented at the 84th Meeting of the Acoustical Society of America, Miami Beach, Florida, November 1972. (Abstract published in the J. Acous. Soc. Am. 53. 1973, p. 319).

[13] Schultz, T. J., "Sound Power Measurements in a Reverberation Room", J. Sound & Vib. 16, 1971, pp. 119-129.

[14] As reported at Session FF: Workshop on Reverberation Room Qualifications for ANSI S1.21, 86th Meeting of the Acoustical Society of America, Los Angeles, California, October 30-November 2, 1973.

[15] Andres, H. G., "A Law Describing the Random Spatial Variation of the Sound Field in Rooms and its Application to Sound Power Measurements", Acustica 16, 1966, pp. 278-294.

In Section 2 above, eq. (9) provides a series expansion for the variance of sound power determinations when using a reference source. The expansion is valid when the normalized error of squared pressure determination for the reference source, ε_r, is less than unity. Under what conditions is this assumption valid? Though we cannot answer the question completely at this time, we can provide some insight. Consider σ_r which is the standard deviation of ε_r. When σ_r is less than unity, ε_r will usually (but not always) be less than one also. The advantage of this approach is that we can make some statements about the size of σ_r.

If an isolated room mode is excited, the variance ε_r^2 depends on the mode type. The variance is less than unity for an axial mode, and greater than unity for an isolated tangential or oblique mode. With a pure tone reference, the risk of exciting an isolated mode diminishes rapidly with frequency. The expected number of modes excited by a pure tone source is given by the index of modal overlap. When the modal overlap index is high, the limiting value for variance with pure tone excitation is $\varepsilon_r^2 = 1$. Normally, the reference source will be broad band rather than pure tone. If the band-width is such that at least two or three modes of different frequencies are substantially excited, the variance ε_r^2 will be less than unity, and the expansion of eq. (8) will be valid.

In order to assess the size of σ_r in terms familiar to workers in acoustics it is useful to relate the normalized standard deviation of squared pressure to the corresponding standard deviation of sound level (dB). This relationship depends on the probability distributions of squared pressure. When many modes are excited, the probability distribution of squared pressure approaches the Chi-square distribution. The distribution of sound levels may then be found by probability transformation. Table A1 provides means and standard deviations of sound level based upon probability transformation of the Chi-square distribution. The results apply to reverberation chambers at frequencies above the Schroeder frequency and in regions remote from the source and from room boundaries. To use this table, the effective number of pure tones, N must first be determined. The effective number of tones is given by

$$N = 1/\sigma_{p^2}^{\,2}$$

i.e., the reciprocal of the spatial variance of squared pressure. Formulas for $\sigma_{p^2}^{\,2}$ are given in [A.1]. The transformation is taken from [A.2].

For N = 1 tone, $\sigma_{p^2}^{\,2} = 1$. The table shows that the expected value of mean level (obtained by averaging sound level readings) is 2.51 dB below the level corresponding to mean squared pressure. In other words, level averaging biases the estimated mean squared pressure. The expected value of bias is largest for the case of excitation with a single pure tone.

For N = 1 tone, the standard deviation of level is 5.57 dB. This corresponds to a standard deviation of squared pressure of unity, and therefore sheds some light on the assumption of eq. (8). It must be remembered that this table assumes that many modes are excited. If only a few modes are excited, the result here is only an approximation to the true case.

The standard deviation of level is greatest for excitation with a single pure tone. For two tones of equal mean square pressure, the standard deviation drops to 3.49 dB.

For flat spectrum noise excitation of bandwidth B, the effective number of tones is given by

$$N \doteq 1 + BT_{60}/6.9.$$

For example, in a room having a reverberation time of 6.9 seconds driven by a source with bandwidth 10 Hz, N = 11. The table shows a bias of 0.20 dB and a standard deviation of 1.34 dB for this case.

Table A1. Statistical Properties of the Random Variable, $Y = 10 \ Log_{10}(I)$

Effective No. of Tones (N)	Correction Factor Mean (dB)	Standard Deviation (dB)
1	2.5068	5.5700
2	1.1742	3.4877
3	0.7636	2.7293
4	0.5654	2.3137
5	0.4487	2.0431
6	0.3719	1.8493
7	0.3176	1.7018
8	0.2771	1.5847
9	0.2457	1.4888
10	0.2208	1.4084
11	0.2004	1.3398
12	0.1835	1.2803
13	0.1692	1.2280
14	0.1570	1.1817
15	0.1464	1.1403
16	0.1371	1.1029
17	0.1290	1.0690
18	0.1218	1.0380
19	0.1153	1.0096
20	0.1095	0.9834
25	0.0874	0.8773
30	0.0728	0.7996
35	0.0623	0.7394
40	0.0545	0.6910
45	0.0484	0.6510
50	0.0436	0.6173
55	0.0396	0.5883
60	0.0363	0.5630
65	0.0335	0.5408
70	0.0311	0.5209
75	0.0290	0.5032
80	0.0272	0.4871
85	0.0256	0.4724
90	0.0242	0.4591
95	0.0229	0.4468
100	0.0218	0.4354
200	0.0109	0.3075
300	0.0072	0.2509
400	0.0054	0.2173
500	0.0043	0.1943
600	0.0036	0.1774
700	0.0031	0.1642
800	0.0027	0.1536
900	0.0024	0.1448
1000	0.0022	0.1374

References for Appendix A

[A.1] Lubman, D., "Precision of reverberant sound power measurements", to be published in the J. Acous. Soc. Am.

[A.2] Lubman, D., and Bowers, H., "Decibel Averaging in Reverberant Rooms", LTV Technical Report 0-71200/8TR-130, March 1968. (For information concerning availability, contact D. Lubman & Associates, 23727 Crosson Drive, Woodland Hills, California 91364.)

Appendix B

The following are editorial comments concerning American National Standard S1.21-1972. It is suggested that consideration be given to incorporating these comments into the standard.

1. The last phrase of Section 12.3, page 20 is missing. It should read ". . . procedures of Section 7."

2. In the equations for sample standard deviation (eqs. 1, 5, and 8) the same symbols are used to represent different quantities, i.e., s, n, L_i, L_m. Perhaps these can be subscripted to avoid the real confusion they generate, e.g., s_1, s_2, s_3, etc.

3. The confusion mentioned above extends to Tables 1, 4, 5, 6, and 8. Standard deviations are used without proper identification.

4. The standard deviation mentioned on page 13, 5th line from the bottom of the page, should 5.57 dB (not 5.56 dB).

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This report presents a critical review of American National Standard S1.21-1972, "Methods for the Determination of Sound Power Levels of Small Sources in Reverberation Rooms." This standard, as now embodied, represents a major advance in the state-of-the-art of reverberation room measurement of sound power. This report was prepared in order to identify additional analytical and experimental information needed for further refinement of this standard. This report presents a detailed critique of specific items in the standard. Indications are given of both general research areas for statistical room acoustics and of specific research areas for improved reverberant room sound power measurements.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

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