G. C. Maling, Jr.
K. S. Nordby

Reverberation Chamber Determination of the Acoustic Power of Pure-Tone Sources*

Abstract: A method was developed that is used to determine the acoustic power radiated by pure-tone and "nearly-pure-tone" sources in a reverberation chamber. The 3-dimensional standing wave sound field generated by a pure-tone source is sampled by a microphone that slowly sweeps a circular path in the chamber. The method relates the average value of the sound pressure at the peaks of the "sample" to its effective rms pressure. The acoustic power of the source is then readily calculated from the effective rms pressure, the volume of the chamber and its absorption.

Introduction

An important property of a sound source is the radiated acoustic power. Air-handling devices, rotating machinery, punches, printers, and other mechanisms may be characterized by an acoustic power spectrum, i.e., the acoustic power radiated as a function of frequency. Acoustic wattmeters are not generally available, but methods have been developed[1] for the calculation of the acoustic power from measurements of sound pressure. To determine the radiated power, free-field measurements may be made in an anechoic (reflection-free) chamber. The acoustic power can then be calculated from the sound pressures measured at many points around the source. If measurements are made in a semi-anechoic chamber (an anechoic chamber with a rigid, usually highly reflective floor) the acoustic power may be calculated from sound pressure measurements on a hypothetical hemisphere resting on the floor and enclosing the source. These measurements are, however, very time-consuming.

In this paper a method is presented that permits the determination of the power spectrum when it contains *discrete frequency components*. For this purpose the source is placed in a reverberation chamber, i.e., a room that has highly reflective interior surfaces. The reverberation-chamber method is now frequently specified[2–4] in standards, and good agreement has been obtained[5,6] between power-level determinations in free-field and in reverberation chambers for broad-band noise sources. However, when the sources radiate pronounced single-frequency or narrow-band energy, the reverberation-chamber method has not been used widely, primarily because of the difficulty in the interpretation of measured data.

There are two major differences between the sound fields produced by broadband and pure-tone (single frequency) sources in a reverberation chamber. First, the sound pressure produced by a broadband source in a reverberation chamber is practically independent of position within the chamber, provided that the source is more than one wavelength from the nearest room surface. The acoustic power radiated by a broadband source can then be determined from a few sound pressure measurements, the chamber volume, and its average absorption coefficient. If, however, the source radiates one or more pronounced single-frequency components, a complicated sound pressure interference standing wave pattern is generated in the chamber. This pattern must be analyzed in order to determine the acoustic power radiated. Second, the radiation impedance of a single-frequency source in a reverberation chamber is not always the same as its radiation impedance in a free field. Therefore, the acoustic power radiated by the source in a reverberation chamber may not be the same as in a free field.

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The results of analyses and experiments performed to determine the acoustic power of sources that generate predominating single-frequency or narrow-band acoustic energy in a reverberation chamber are presented. In the past, several methods have been proposed for analyzing the amplitude of the spatial variations of sound pressure to determine the acoustic power. The method described in this paper is based on the determination of the root-mean-square pressure in a reverberation chamber through an analysis of the interference pattern. One advantage of this method is that commonly available instrumentation can be used for the analysis.

The radiation impedance of a pure-tone source usually varies with the source location in a reverberation chamber. The reverberation chamber sound power output of a pure-tone source is therefore not necessarily the same as its free field output. Therefore, a theoretical analysis is first presented for determining the variations in radiation impedance of a point source (monopole) in a reverberation chamber. The analysis is based on a definition of the radiation impedance for a source proposed by R. V. Waterhouse.[7] The real part of the radiation impedance in the reverberation chamber is computed for many source positions with the aid of a digital computer. These variations are then treated statistically. The conclusion of the analysis is that when many normal modes (to be defined) are excited in a reverberation chamber the variation in the radiation impedance of the source attributable to reflections is small, and the acoustic power radiated by a pure-tone source averaged over a large number of source positions is the same as the power the source would radiate in free space.

The second section discusses the relationship between the mean-square sound pressure in the chamber and the acoustic power radiated by the source. It is shown that the space-averaged mean-square pressure, which we designate as $\overline{p^2}$, must be established in order to determine the acoustic power radiated.

In the third section, it is shown how the sound pressure pattern obtained by moving a microphone over a circular path in the chamber is analyzed to determine the $\overline{p^2}$. The calibration of two reverberation chambers for pure-tone measurements are described. As an example, measurements made using this method are compared with sound power measurements performed in a semi-anechoic chamber.

In the fourth and fifth sections, the application of the measurement method to practical sources such as fans and blowers is discussed. Air-handling devices are used as examples because they often generate a "nearly pure tone" at the blade passage frequency and its harmonics.

Radiation impedance calculation for a point source (monopole)

To determine the acoustic power radiated by a pure-tone source in a reverberation chamber with adequate accuracy (± 1 dB) and repeatability (± 1 dB) its radiation impedance must be nearly independent of location within the chamber and must not vary significantly with frequency.

The definition of radiation impedance for a source introduced by Waterhouse is used here because the effect of boundaries near a source can be included in the analysis. The radiation impedance, however, has not previously been calculated for a source located in a rectangular reverberation chamber.

As defined by Waterhouse, the radiation impedance for a source is

$$Z = \lim_{k\epsilon \to 0} \left(\frac{p}{U} \right), \tag{1}$$

where
ϵ is the radius of the spherical, omnidirectional source;
k, the wave number, $= 2\pi/\lambda$;
λ is the wavelength of the emitted sound; and
p is the sound pressure.
U is the volume velocity defined by

$$U = \int \mathbf{u} \cdot d\mathbf{s}\,, \tag{2}$$

where $\mathbf{u}$ is the velocity at the surface of the source. The integral is to be taken over the entire source surface.

The impedance Z can be separated into a component Z_0, which is the free-field radiation impedance, and a component Z_r, which is due to reflections from the chamber surfaces. Waterhouse showed that the real parts of these impedances, R_0 and R_r, respectively, are related to the acoustic power radiated by the source as follows:

$$\frac{W}{W_0} = 1 + \frac{R_r}{R_0}, \tag{3}$$

where W is the power output of the source in the reverberation chamber and W_0 is the free-field power output.

We must now determine how R_r varies with source position and frequency within a rectangular reverberation chamber. To find R_r, the ratio between the power output of a small monopole source in a reverberation chamber and its free-field power output is first calculated. The acoustic power, W, is given by[8]

$$W = \tfrac{1}{2}\,\mathrm{Re}\left[\int p^* \mathbf{u} \cdot d\mathbf{s} \right], \tag{4}$$

where complex notation has been used for the pressure field and harmonic time dependence for the field has been assumed in the form $[p(x, t) = p(x)e^{i\omega t}]$.

The symbol * denotes the complex conjugate, and "Re" indicates that only the real part of the integral is to be taken. The integral is to be taken over any surface that completely encloses the source. For this investigation, this surface is taken as the interior surface area of a reverberation chamber. The ratio W/W_0 has been determined in another

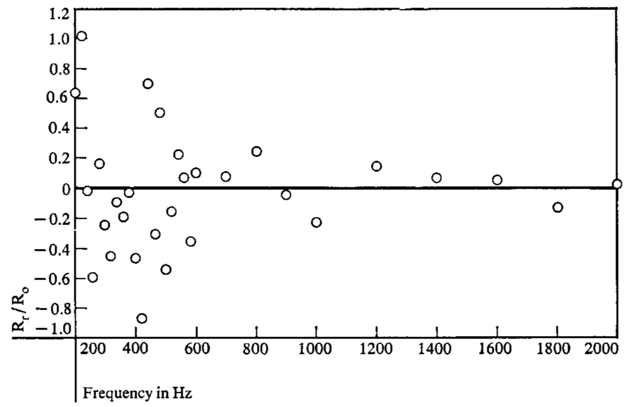


Figure 1 The space-average ratio R_r/R_0 vs frequency for the reverberation chamber in the IBM Poughkeepsie Acoustics Laboratory.

paper[9], and is combined with Eq. (3) to give the ratio R_r/R_0.

$$\frac{R_r}{R_0} = \left[\pi\beta S \sum_{l,m,n} \left(\frac{\epsilon_l\epsilon_m\epsilon_n}{V}\right)^2 \times \frac{\cos^2\frac{l\pi x_0}{L_x}\cos^2\frac{m\pi y_0}{L_y}\cos^2\frac{n\pi z_0}{L_z}}{(k^2-k_0^2)^2+\left[2k\beta\left(\frac{\epsilon_l}{L_x}+\frac{\epsilon_m}{L_y}+\frac{\epsilon_n}{L_z}\right)\right]^2}\right] - 1\,, \quad (5)$$

where

$$k_0^2 = \left(\frac{l\pi}{L_x}\right)^2 + \left(\frac{m\pi}{L_y}\right)^2 + \left(\frac{n\pi}{L_z}\right)^2 ;$$

S is the surface area of the chamber; k, the wave number; x_0, y_0, and z_0 are the coordinates for the source location within a rectangular reverberation chamber, and the sum in Eq. (5) is to be taken over all integral values of l, m, and n; L_x, L_y, and L_z are the chamber dimensions; V is the chamber volume, and $\epsilon_0 = 1$, $\epsilon_l = 2$ for $l \neq 0$, etc.; and β is the normal admittance of the chamber surfaces.

The resonance denominator in Eq. (5) is an approximation valid for highly reflective walls ($\beta \ll 1$), an essential characteristic of a reverberation chamber.

Because of the large number of terms involved in Eq. (5), a high-speed computer is required for its evaluation. The value of R_r/R_0 is of particular interest at low frequencies, where large fluctuations in the ratio may occur. Detailed calculations will be presented in another journal.[9]

Note that the sum of Eq. (5) is dominated by those terms for which $k \doteq k_0$ because the "damping term"

$$\left[2k\beta\left(\frac{\epsilon_l}{L_x}+\frac{\epsilon_m}{L_y}+\frac{\epsilon_n}{L_z}\right)\right]^2$$

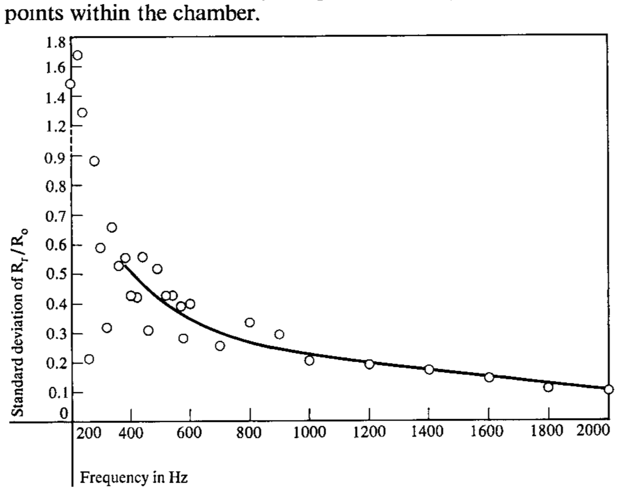
is in general small. For perfectly rigid and reflective walls the "damping term" is zero.

When a great number of modes are excited within the chamber, the sum in Eq. (5) can be converted into an integral and determined, provided R_r/R_0 is averaged over all possible source positions. The result of this integration is that $R_r/R_0 = 0$.

Therefore at frequencies where a great number of modes is excited in the chamber, the *space-averaged power output* of a sound source is the same as the free-field power output. However, the ratio R_r/R_0 is a function of source location. Therefore, the power radiated at any one source location usually differs from the free-field radiated power. To determine the magnitude of these variations, the ratio R_r/R_0 and its standard deviation have been computed from Eq. (5) for the reverberation chamber at the IBM Acoustics Laboratory in Poughkeepsie, N. Y. The results are shown in Figs. 1 and 2.

Large variations in R_r/R_0 occur at low frequencies, but above 500 Hz the ratio R_r/R_0 averaged over many source positions varies only ± 0.25 with frequency. This corresponds to a variation of approximately ± 1 dB in the ratio of W/W_0. The standard deviation of R_r/R_0 decreases rapidly with increasing frequency. Using these data and statistical methods,[10] one can calculate how many source positions are required to determine W with a desired degree of accuracy.

Figure 2 Standard deviation of the ratio R_r/R_0 for the reverberation chamber in the IBM Poughkeepsie Acoustics Laboratory. The ratio was determined by computation of R_r/R_0 at 50 random points within the chamber.



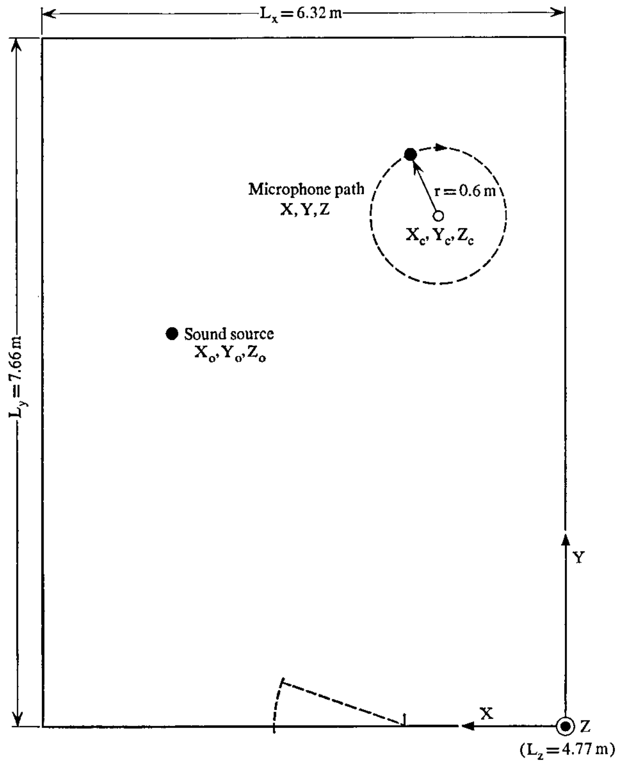


Figure 3 Plan view of the experimental setup in a reverberation chamber.

Relationship between radiated power and mean-square sound pressure

In the previous section we have shown that, for frequencies above 500 Hz, the radiation impedance seen by a pure-tone monopole in a typical reverberation chamber is nearly the same as in a free field. For this reason a reverberation chamber determination of radiated acoustic power appears to be feasible. Many sources emit a combination of broad-band noise and pure tones or a narrow band of noise. The determination of their radiated power can be made much more rapidly in a reverberation chamber than in an anechoic or semi-anechoic chamber.

The relationship between W and $\overline{p^2}$ must next be determined. For a monopole, it may be found by expressing the pressure field as a sum over the appropriate eigenfunctions. The details have been presented by Morse and Ingard.[11] The expression for the pressure field within the chamber is:

$$p = \frac{i\omega Q_0}{V} \sum_{l,m,n} \epsilon_l \epsilon_m \epsilon_n \frac{\left(\cos\frac{l\pi x}{L_x}\cos\frac{l\pi x_0}{L_x}\cos\frac{m\pi y}{L_y}\cos\frac{m\pi y_0}{L_y}\cos\frac{n\pi z}{L_z}\cos\frac{n\pi z_0}{L_z}\right)e^{-i\omega t}}{k^2 - \left(\frac{l\pi}{L_x}\right)^2 - \left(\frac{m\pi}{L_y}\right)^2 - \left(\frac{n\pi}{L_z}\right)^2 - 2ik\beta\left(\frac{\epsilon_l}{L_x} + \frac{\epsilon_m}{L_y} + \frac{\epsilon_n}{L_z}\right)} \quad (6)$$

Here Q_0 is the strength (mass flow/second) of the monopole source. All other quantities have been defined previously.

Morse[12] has shown that $\overline{p^2}$ can be found when a large number of modes exist in a chamber by conversion of the appropriate sum of Eq. (6) to an integral. Using this result, and the expression for the free-space output of a monopole, $W_0 = \omega^2 Q_0^2/8\pi\rho c$, it can be shown that

$$W = \overline{p^2}\,\frac{\overline{\alpha}S}{4\rho c}\,. \quad (7)$$

The same result would be obtained from diffuse field theory.[13] The approximation[14] $\beta = \overline{\alpha}/8$ for $\beta \ll 1$, where $\overline{\alpha}$ is the average absorption coefficient[1] of the chamber surfaces, has been used in Eq. (7).

The acoustic power output of the source is related to $\overline{p^2}$ as shown by Eq. (7) and can be determined from a measurement of the sound pressure, the average absorption coefficient, the chamber surface area and the characteristic impedance of air.

A precise determination of the mean-square pressure requires pressure measurements at several locations within a chamber. Waterhouse[15] has studied in detail the statistical properties of the mean-square pressure measured at random locations within a chamber. He derived criteria that express the accuracy with which $\overline{p^2}$ can be determined by measuring the mean square pressure at a given number of points chosen at random within a reverberation chamber. Excellent agreement was obtained between theoretical and measured results.

The method presented in this paper differs from that of Waterhouse in two respects. The sound pressure interference patterns are measured by a microphone sweeping circular paths, which is more suited for automatic recording, and $\overline{p^2}$ is determined from an analysis of the *peaks* of the sound pressure interference patterns.

Reverberation chamber calibration for pure-tone measurements

Calibration data were obtained with a special sound source in a reverberation chamber which is a parallelepiped measuring 4.77 × 6.32 × 7.66 meters (volume = 230 m³). The reverberation times measured in one-third-octave bands vary from 10 seconds at 250 Hz to 2 seconds at 8,000 Hz.

Figure 3 shows a plan view of the experimental setup. The sound source is a horn driver attached to a cast-iron

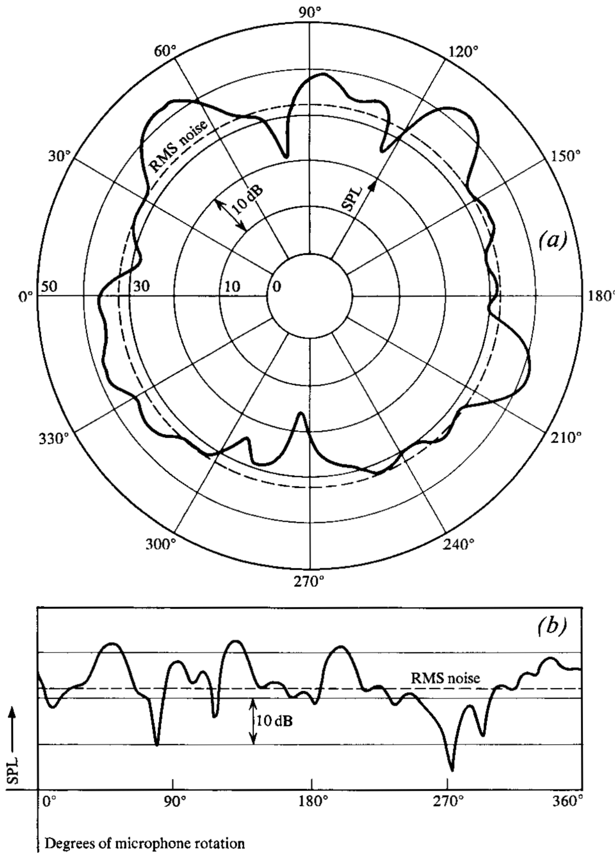


Figure 4 Typical SPLIP when the chamber is excited by a 1-kHz sinusoidal wave (see text).

tube 0.3 meter long by 0.035 meter i.d. The tube is filled with steel wool to produce a high-impedance source; this also damps high-frequency cross-modes in the tube.

When the source emits a pure tone, an interference or standing wave pattern is produced in the chamber. This type of pattern may be called a (single frequency) sound pressure level interference pattern (SPLIP). It is analyzed to determine the space-averaged sound pressure level (SPL) in the chamber. The SPL is defined by

$$\mathrm{SPL} = 20 \log \left(\frac{p}{p_{\mathrm{ref}}} \right), \tag{8}$$

where p is the rms sound pressure, and p_{ref} is the reference rms sound pressure, $2 \times 10^{-5} N/m^2$. Most acoustical instrumentation is designed for direct measurement of the SPL rather than the mean-square pressure. To measure the SPLIP, a 1/2 inch condenser microphone is moved along a circular path of 0.6-meter radius. The time required for one 360-degree sweep is 80 seconds. The source location and the location of the circular paths were varied in order to obtain data which may be used to determine averages over source and receiver locations. For the data presented here, the source was on the floor (position I) and at 0.93 meter above the floor (for positions II and III). For the three pairs of source and circular path positions used, the circular paths were always kept at 1.5 meters above the floor.

Figure 4a shows a typical example of the SPL along a circular path (solid curve) when the chamber is excited by a 1 kHz sinusoidal source. The basic problem is to determine the mean-square pressure in the chamber from these patterns. In this paper it is shown that the average value of the SPL's at the maxima of the interference patterns may, after application of a correction factor, be used to estimate the space-averaged SPL. The correction factors are obtained by a chamber calibration procedure that is described below.

The dotted circle in Fig. 4a is the "equivalent rms" SPL and is obtained by a 360° sweep of the microphone when the source is excited by a 6% bandwidth noise voltage. The rms value of the noise voltage is equal to the rms value of the 1 kHz sinusoidal voltage that produces the SPLIP. Both the electrical impedance and the radiation impedance of the horn driver can be considered constant over a 6% bandwidth. Therefore, the acoustical power outputs are the same for both signals.

Figure 4b shows a rectilinear plot of the data shown in Fig. 4a. Rectilinear plots are more convenient for both the data analysis required to calibrate the chamber and for the determination of the acoustic power radiated by pure-tone sources. Repetitive sweeps (SPLIP's within ± 1 dB at the pressure maxima) over the same path can be obtained only if the source frequency and the speed of sound are kept constant within one part in 10^6. The important parameter is the wave number $k = \omega/c$. Changes (e.g., thermal variations) in the chamber dimensions will affect the SPLIP in the same manner as changes in frequency or sound velocity. If the reverberation chamber door is opened and closed, the room must be allowed to come to the required thermal equilibrium to obtain repetitive SPLIP's.

The particular feature of the SPLIP used for the chamber calibration is the SPL at the maxima of the interference pattern. An *amplitude distribution function* (histogram) of these maxima may be established, although only the mean value of the distribution is actually used in the analysis. To obtain, for example a 1-kHz calibration, the chamber is excited by eight different frequencies between 990 and 1010 Hz. Since approximately 13 SPL maxima are obtained per sweep at each frequency, 104 data points are obtained for one pair of source and microphone path locations. Distribution curves of the SPL maxima were found to be nearly Gaussian. A typical histogram is shown in Fig. 5. The mean level (63.5 dB) and the "equivalent rms" level (61.4 dB) are indicated on the abscissa. It can be seen that for this example, the "equivalent rms" level is approximately 2 dB below the mean level. The procedure is repeated at this frequency for two other pairs of source and microphone path locations. Two more calibration values, i.e., the difference between the mean of the SPL maxima and the "equivalent rms" levels, are thus obtained for 1 kHz.

Calibration data for the Poughkeepsie reverberation chamber are presented in Fig. 6. At 1 kHz, the value is 2.2, 3.5, and 2.1 dB for the paired source and path locations I, II, and III. Calibration data for other frequencies are obtained in the same manner as for 1 kHz. The number of sweeps may be reduced with increasing frequency because the number of SPL maxima per sweep is proportional to the excitation frequency of the chamber. For example, one sweep is adequate at 8 kHz for each pair of source and path positions, while 32 are desirable at 250 Hz if a 0.6-m sweep radius is used.

The calibration data in Fig. 6 are used to determine the "equivalent rms" SPL when the SPLIP from a source under test has been analyzed and the mean value of the SPL maxima has been established in the manner described.

The mean-squared pressure in the chamber is then determined by inverting Eq. (8):

$$\overline{p^2} = p_{\text{ref}}^2 \log^{-1}\left(\frac{\text{"equivalent rms" SPL}}{20}\right). \qquad (9)$$

The acoustic power radiated by the source can then be determined by Eq. (7) if the average absorption coefficient is known. An estimate of $\bar{\alpha}$ may be found from the room dimensions and the reverberation time by using the relation[13]

$$\bar{\alpha} = 0.16\frac{V}{TS}, \qquad (10)$$

where V is the room volume (m^3), S is the surface area (m^2), and T is the reverberation time (sec).

An alternative method for the determination of the acoustic power is to use a reference sound source, usually a broadband source whose power spectrum is known from a previous calibration. The value of $\overline{p_r^2}$ for the reference source is measured in a frequency band at or near the frequency generated by the pure-tone source. If the acoustic power radiated by the reference source in this band is known to be W_r, the power output of the pure-tone source may be determined from

$$W = W_r\left(\frac{\overline{p^2}}{\overline{p_r^2}}\right). \qquad (11)$$

Power determination for a single-frequency source

Standard methods have been developed[1] for the determination of the power output of a sound source in an anechoic or semi-anechoic chamber. It is, therefore, of interest to compare the results obtained by the method developed here with results obtained with standard methods.

The sound source described in the previous section was

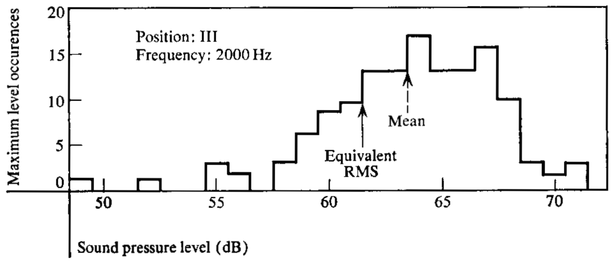


Figure 5 Typical distribution curve for SPL maxima.

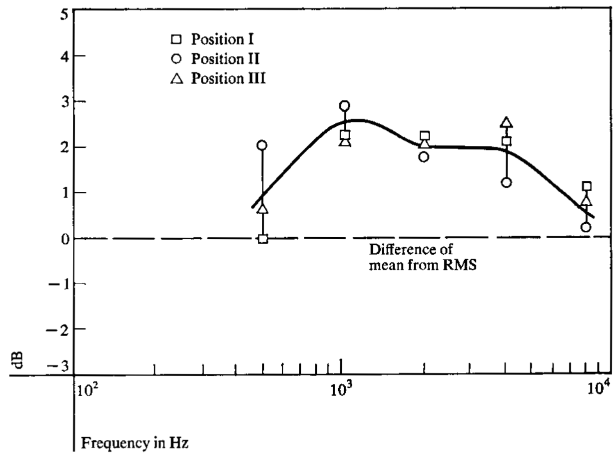


Figure 6 Calibration data for the reverberation chamber in the IBM Poughkeepsie Acoustics Laboratory.

placed on the floor in a semi-anechoic chamber. The radiated acoustic power was determined from sound pressure measurements at eight standard points around the source. The results were corrected for the effect of the floor (reflecting plane). The acoustic power levels (PWL's) generated by a 1-volt rms input signal to the source are shown in Fig. 7 for six different frequencies. The PWL is defined by PWL $= 10 \log(W/W_{\text{ref}})$ where W is the power in watts and W_{ref} is the reference power, 10^{-13} watts.

The same source was then placed at three source positions chosen at random in the reverberation chamber. SPLIP's were obtained at each frequency and the data treated according to the method described in the previous section. The power radiated was determined from the mean-square pressure through the use of a broadband reference sound source of known power output. The data are shown in Fig. 7. The two determinations are in reasonably good agreement, particularly when one considers that variations in power output in a reverberation chamber exist due to changes in radiation impedance as shown in Fig. 1.

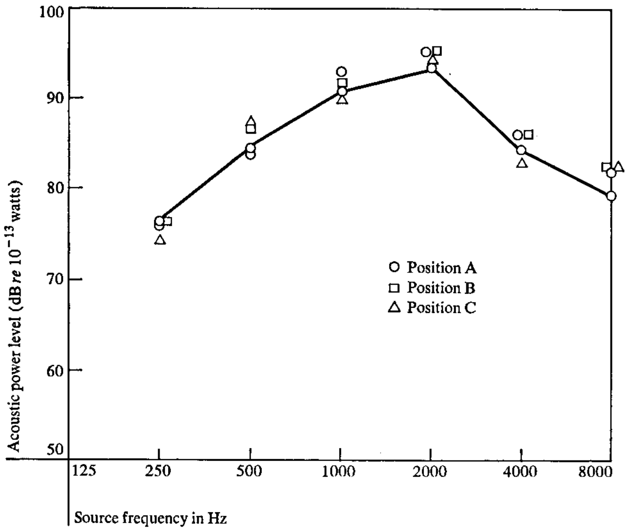


Figure 7 Comparison of acoustic power levels for a pure-tone source measured in a reverberation chamber and in a semi-anechoic chamber.

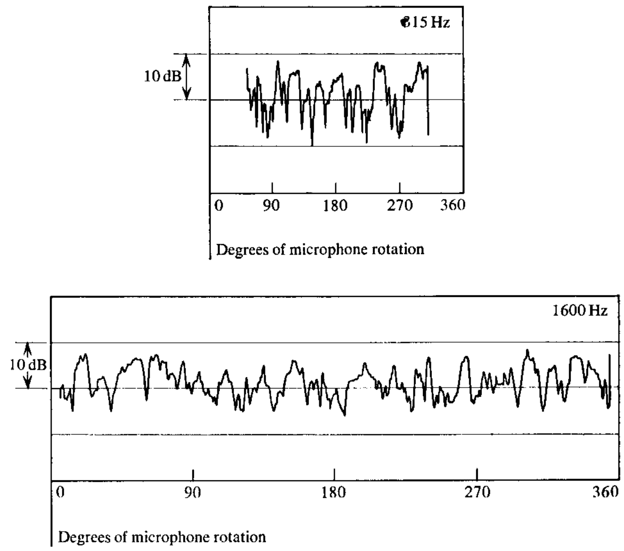


Figure 8 Typical pressure patterns for an axial flow device (upper) and a centrifugal blower (lower).

Power determination for "nearly pure-tone" sources

Many sound sources produce a broadband spectrum as well as predominating single frequency components. For example, air-moving devices such as centrifugal blowers and axial flow fans produce both broadband noise and nearly pure tones at the blade-passage frequency and its harmonics. Slow variations in motor speed cause the frequencies of the nearly pure tones to vary slightly. The method described here may also be used to determine the acoustic power of such "nearly-pure-tone" sources. The major difference between the SPLIP's generated by a pure-tone and a nearly-pure-tone source is in the magnitude of the temporal variations of the interference patterns. In the pure-tone case, identical (within 1 dB at SPL maxima) interterence patterns can be obtained on successive sweeps of the microphone if extreme care is exercised in performing the experiments. For example, to obtain repetitive patterns, it is necessary to keep the frequency constant within one part of 10^6 and to allow the chamber to stabilize thermally after closing the chamber door.

In the case of nearly pure tones, as generated by centrifugal blowers and axial flow fans, there is always a slow variation in SPL at any fixed point in the chamber. The slow variations in fan speed may be caused by temperature and turbulent velocity fluctuations within the chamber (even when the supply voltage is well regulated). To keep the variations of the maxima small for a 517-Hz SPLIP, caused by a 10-bladed fan running at 3100 rpm, the speed regulation would have to be better than 0.1%.

In Fig. 8, typical SPL patterns are shown for an axial fan and a centrifugal blower. The upper curve shows the SPL for the axial flow fan. It has a nearly pure-tone component at approximately 315 Hz. The pattern is much more irregular than the patterns obtained for pure-tone sources. The lower pattern was obtained from measurements of a centrifugal blower. This blower produces a nearly pure tone at the blade-passage frequency (~1600 Hz).

These data were taken with a 0.88-meter radius microphone path in order to obtain more maxima for one microphone sweep than were obtained in the pure-tone case.

As mentioned previously, there are slow temporal variations in the SPL of nearly pure-tone sources at any one point in the chamber. It is, therefore, necessary to determine if the statistical properties of the SPL patterns change on successive sweeps. For the PWL determination only the mean value of the statistical distribution of the SPL maxima is required. Some typical data are shown in Fig. 9. The upper Figure represents the mean value of the maxima of the SPL's for five successive sweeps using one microphone path. The lower curve shows the SPL variations as a function of the locations of the microphone path and the sound source. Figure 9 shows that the SPL differs from the mean value by at most 2.5 dB. In practice, one would want to average over data taken at two or three different microphone path locations. All these data are for the axial flow device.

Data obtained on a centrifugal blower are shown in Fig. 10. Here the mean of the peak SPL distribution has been

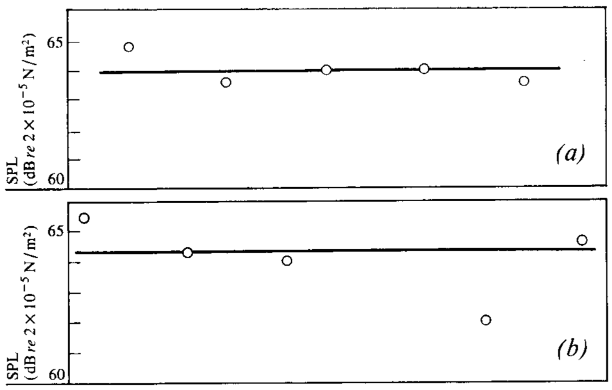
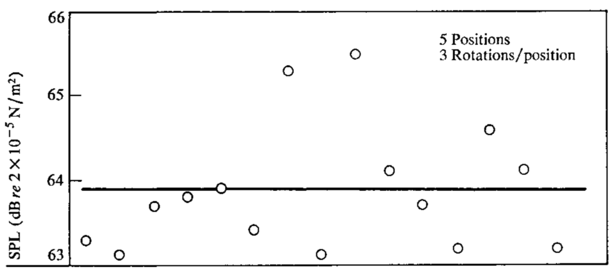


Figure 9 (Upper) Mean value of the maxima of the sound pressure level for five successive microphone rotations. (Lower) Variation as a function of the position of the microphone path and sound source.

Figure 10 Mean value of the maxima of the sound pressure level as a function of source/microphone path positions and successive rotations.



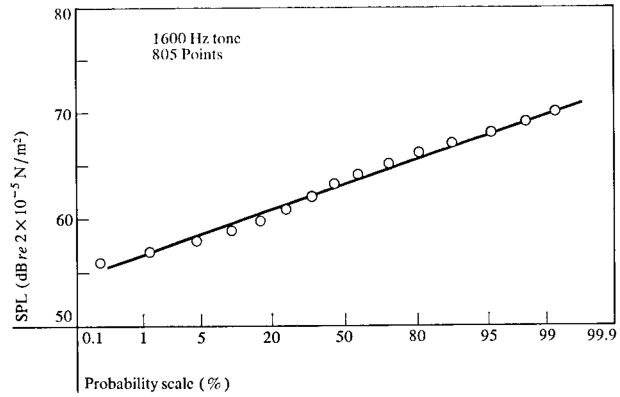
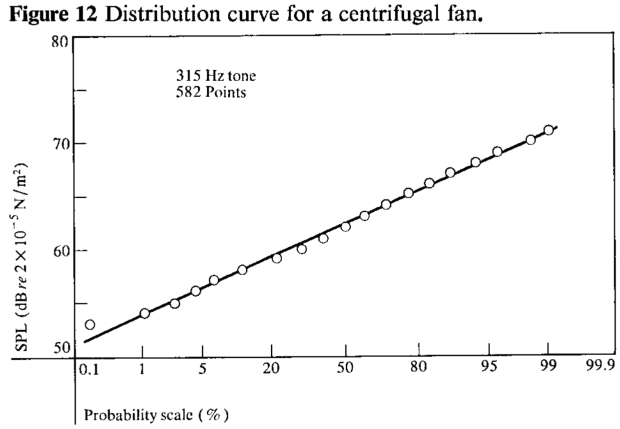


Figure 11 Distribution curve for an axial flow fan.

Figure 12 Distribution curve for a centrifugal fan.



plotted for both a change of source/microphone path locations and for successive sweeps. A total of 15 different data points was obtained. There is a somewhat larger scatter in this case, but all points fall within approximately ± 1.5 dB of the average (63.9 dB).

In order to determine the acoustic power radiated at the blade-passage frequency, these data must be related to the "equivalent rms" SPL in the chamber. This is done by using the calibration data shown in Fig. 6. For example, at 1600 Hz, one has to subtract approximately 2 dB from the mean value of the peak SPL distribution in order to obtain the "equivalent rms" SPL. The acoustic power radiated by the source is then calculated as before by using Eq. (7) or Eq. (9).

A further topic of interest is the amplitude distribution of the peak SPL's. For pure tones the distribution is very nearly Gaussian when plotted on an SPL basis. Distribution curves for the two examples used in this paper have been determined and are shown in Figs. 11 and 12. The ordinate gives the SPL's and the abscissa is a Gaussian probability scale. The data fall very nearly on a straight line. Hence, the distribution curve is close to Gaussian for nearly pure-tone sources as well as for pure-tone sources.

Another series of experiments was performed to demonstrate the usefulness of these techniques. The acoustic powers radiated by nine axial flow fans were determined in a reverberation chamber and in a semi-anechoic chamber. Most of the units produced a pronounced pure tone at the blade-passage frequency. When large spatial SPL variations occurred in the reverberation chamber, the levels were treated according to the method described. A comparison between the PWL's determined in a reverberation chamber and in a semi-anechoic chamber is shown in Fig. 13. The 194 m^3 reverberation chamber at the IBM Laboratories in Endicott, New York, was used for these studies. A calibration curve for this chamber is shown in Fig. 14. The semi-anechoic chamber data were obtained on the same fans at the IBM Laboratory in Boeblingen, Germany.

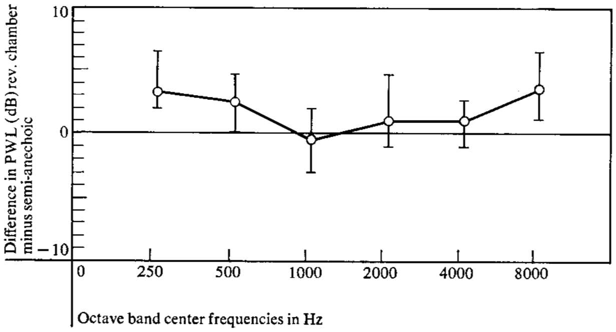


Figure 13 Differences between power levels in a reverberation chamber and in a semi-anechoic chamber for nine fans.

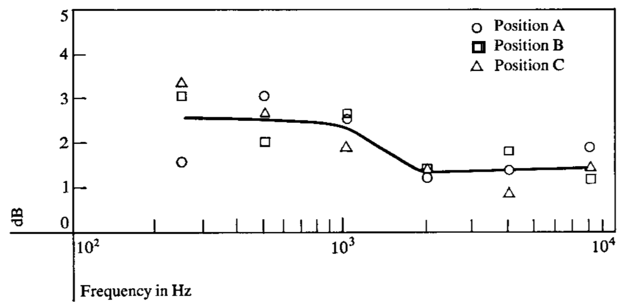


Figure 14 Calibration data for the reverberation chamber at the IBM Laboratory, Endicott, New York.

Conclusions

Measurement of the acoustic power radiated by a pure-tone or "nearly-pure-tone" source in a reverberation chamber is feasible and will for most sources take considerably less time than in a semi-anechoic chamber. However, the power radiated is necessarily not the same as in a free-field because it depends on the source position within the chamber particularly at low frequencies. The mean-square sound pressure in the chamber must be determined, and the relationship between this mean value and the acoustic power output of the sound source must be calculated.

These factors have not been adequately addressed in the past and many of the mathematical expressions require lengthy computations that can be performed only with digital computers.

In this paper, these factors have been studied, the objective being development of a practical method for determination of the power output of a pure-tone source in a reverberation chamber. Fluctuations in radiation impedance in a reverberation chamber have been studied theoretically, and detailed computations for a particular chamber have been made. It has also been found that at high frequencies, relationships valid for diffuse fields may be used to find the relationship between the space-averaged, mean-square pressure and the radiated acoustic power. Finally, a method of interpreting an interference pattern has been proposed that may be used to determine $\overline{p^2}$ with commonly available instrumentation. The method has been applied to several noise sources and comparisons were made between results in a reverberation chamber and in a semi-anechoic chamber.

The techniques described here will certainly be improved by future work. For example, the possibility of determining $\overline{p^2}$ with special-purpose instrumentation must be studied. The SPL space-averages used in the present paper have been determined for a relatively short microphone path and for a limited number of paths. Data are needed for many paths within the chamber, and a criterion must be developed that expresses the accuracy of an estimate of $\overline{p^2}$ in terms of frequency and microphone path length. A smoothing of the radiation impedance fluctuations should lead to further reductions in the time required to perform these analyses. For this purpose, the effect of moving vanes (which are used in many reverberation chambers) must be studied. However, no such experimental or theoretical data are available at this time. It is hoped that this paper will stimulate other workers to investigate these and related problems.

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