Acoustical properties of the National Bureau of Standards anechoic chamber

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The acoustical properties of the large anechoic chamber at the National Bureau of Standards were investigated by two methods over the frequency range 40–63000 Hz. In the first method described, deviations of mean-square sound pressure from an assumed inverse square law were measured as a sound source and microphone were moved apart. Over most of the frequency range, the deviations were found from a least-squares curve-fitting procedure by means of digital-computer processing of the data. The effective acoustic centers of the sources were obtained as a by-product of the procedure. In the second method, the source and microphone were kept at a fixed separation as they were moved together across the chamber, and deviations from the mean value of the sound pressure level were estimated from recordings. The significances of the two methods are discussed with a view towards their application.

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INTRODUCTION

In order to evaluate data obtained from measurements of sound pressure in an anechoic chamber, the quantitative effects of sound reflections and scattering within the chamber must be known. It was mainly for this reason that the acoustical properties of the large anechoic chamber at the National Bureau of Standards were investigated.

Two methods were used. (1) Measurements were made of sound pressure while a sound source and microphone were moved apart, and deviations of the sound pressure levels from the inverse square law calculated from these measurements. (2) The source and microphone were moved across the chamber at a fixed separation, and deviations from the average value of sound pressure levels estimated from recordings of the levels.

It was taken for granted that the reflections and scattering from the walls were strong enough, when superimposed on the sound field of the source, to cause measurable deviations in sound pressure levels from those of the true source field. On the other hand, it was assumed that the reflections were not strong enough to cause a measurable change in the total field, including the sound power, radiated by the source.

For both methods, measurements were made at various frequencies for steady sounds, harmonic in time. The first method, which is considered more useful, supplies quantitative information that can be used to estimate the maximum errors that would result in making sound pressure measurements in the chamber for specified locations of sound sources and receivers. The second method provides information on how the measured sound pressure will vary due to reflection and scattering for different positions in the room of the source and microphone. Sources and microphones, omnidirectional to the greatest extent possible, were chosen so that the effect of the reflective characteristics of all room surfaces and features (such as the wire-mesh floor) would be taken into account.

The results of the inverse square law measurements are stated in terms of the maximum deviations from the free-field values as obtained from the curve-fitting procedures described in Section III. In addition, the standard deviation of the residuals is given for frequencies in the range 1–10 kHz. Over this range, curve-fitting procedures could be used over the entire distance traversed by the microphone because of the relatively small deviations, their close spacing, and their essentially random nature.

I. DESCRIPTION OF ANECHOIC CHAMBER

The anechoic chamber is constructed as a shell within a shell. Outer walls of 0.30-m-thick reinforced concrete are separated from 0.30-m-thick inner walls by a 1.3-m air space. The inner shell rests on 52 steel coil springs to attenuate ground vibrations and thus add to the acoustical isolation. The resonance frequency for vertical oscillations of the inner shell resting upon the springs is about 3 Hz.

The free-field dimensions of the chamber are 6.7 ×10.0×6.7 m high. The absorptive treatment consists of glass wool wedge modules, installed with their front edges in alternating directions, on all six inner surfaces of the room. Access to apparatus within the room is provided by a wire-mesh floor of 2.4-mm-diam stranded steel cables spaced on 5.1-cm centers. The floor is located 1.6 m above the tips of the floor wedges and 5.0 m below the tips of the ceiling wedges. Figure 1 shows a detailed sketch of a wedge module and Fig. 2 an overall view of the chamber in which the wedge-module arrangement, the wire-mesh floor, and recessed ceiling lights can be seen. On the chamber door, which swings inward, and on the walls adjacent to the door, the front edges of the wedge modules are parallel to each other to allow them to interlace when the door is opened.

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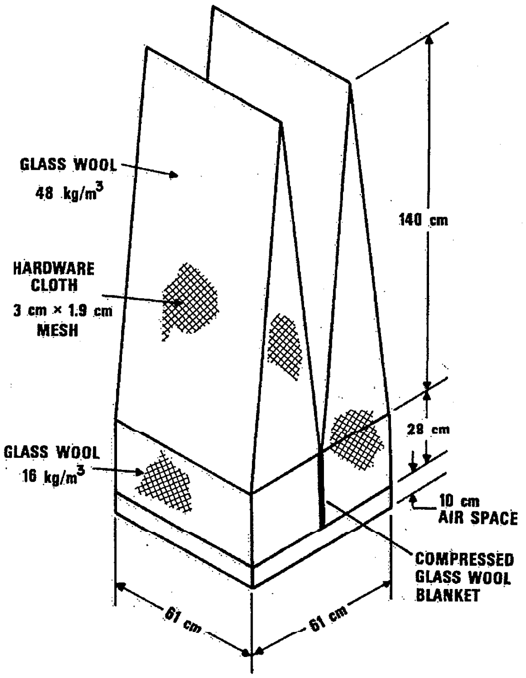

FIG. 1. Wedge module used in NBS anechoic chamber.

Additional accessories in the room include power outlets, communication-line outlets, air-conditioning outlets, and a number of rigid supports for instruments on all six room surfaces. A nylon mesh screen is located just over the tips of the floor wedges to keep foreign objects from falling between the wedges and to facilitate their retrieval. The air-conditioning ducts are acoustically treated and arranged to minimize aerodynamic flow noise and transmission of building noise. In addition, when the room is in operation, the air flow to the chamber can be shut off and the ducts closed. Humidity control is available to provide a relative humidity of 45%±5%.

To check the uniformity of the wedge materials during construction of the chamber, the reflection coefficients of a number of individual wedges were measured in a plane-wave impedance tube of cross section 20.3 ×20.3 cm. These wedges, which had a base cross section the same size as the tube, had reflection coefficients very much like the prototypes described in Ref. 1. The cutoff frequency, defined as the lowest frequency above which the pressure reflection coefficient for a plane wave at normal incidence does not exceed 0.10, was approximately 45 Hz.

II. INVERSE SQUARE LAW—BACKGROUND AND DISCUSSION

In order to determine the effects of reflection and scattering on sound pressure, an absolute knowledge of the sound field radiated by a source is needed to serve as a reference. But a calculation of the sound field for most practical sources is virtually impossible. This difficulty has led to the use of the inverse square law as a reference scheme for determination of scattering effects. The usage is apparently based on the Sommerfeld principle[2] which states that, in the limit of large distances, the time-averaged squared sound pressure, and also the intensity of the sound, vary inversely as the square of the distance from a steady source. For a spherically symmetrical source, the inverse square variation holds for all distances.

A basic hypothetical method for measuring deviations from the inverse square law is, therefore, as follows. A simple point source of known strength, radiating spherically symmetric waves harmonic in time, and a point, omnidirectional, calibrated microphone are placed in the chamber. The rms sound pressure is measured with the microphone as a function of the distance between source and microphone along a fixed straight line passing through the two points. The sound pressures that would be present in a perfectly anechoic chamber are calculated from the strength of the point source. These pressures vary inversely with distance from the source and the intensity inversely as distance squared from the source; this behavior is usually referred to as the inverse square law.

However, the measured pressures in an actual chamber are affected by sound waves scattered from the wedges, from the wire-mesh floor, etc., as we indicated above. In addition, there is an exponential attenuation of sound pressure due to atmospheric absorption. A point-by-point comparison of the measured and calculated sound pressures would yield deviations from the inverse square law due to scattering, and a systematic departure due to absorption.

Another systematic departure from the inverse square law can limit its usefulness for measurement of reflection and scattering effects in an anechoic chamber. With a sound source of finite size, substantial systematic departures can be expected when the sound pres-

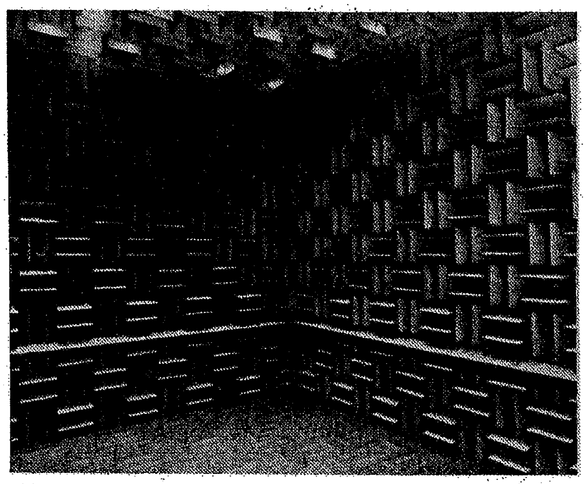

FIG. 2. National Bureau of Standards anechoic chamber, showing features such as the wedge module arrangement, wire-mesh floor, and recessed ceiling lights.

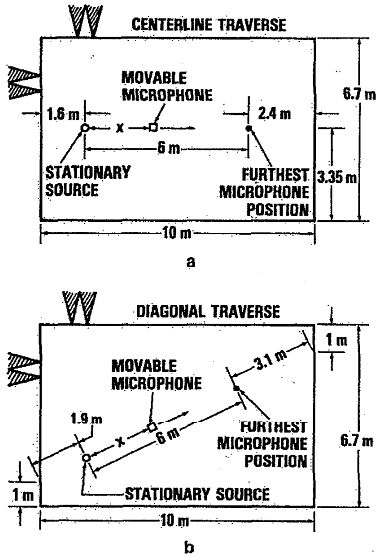

FIG. 3. Plan view of paths traversed in inverse square law measurements with a stationary source and a moving microphone. Both traverses were horizontal and located midway between the floor and ceiling wedges.

sures are measured at distances comparable to its linear dimensions. For a point dipole source, for example, these systematic departures occur at distances from the source that are less than about one wavelength. However, as described below, the systematic effects of absorption can be introduced into the basic hypothetical method outlined previously in this section, leading to an "exponentially attenuated inverse square law."

In addition to these theoretical considerations, there are obvious practical difficulties in carrying out experimentally the hypothetical procedure outlined above. Spherically symmetrical sources and omnidirectional microphones are difficult to achieve practically and source strength is rarely known. For practical sources the rms sound pressure does not, in general, vary inversely with distance from any point whatsoever. However, consider distances large compared to the linear dimensions of the radiating source, but small enough so that atmospheric absorption does not predominate. Then sound pressure does vary approximately inversely with distance from a point which we shall call the "effective acoustic center." Comparison of the measured pressures with the calculated pressures of spherical waves issuing from the effective center will then yield a measure of the deviations arising from scattering effects, as well as deviations arising from systematic departures of the actual sound field from the hypothetical inverse square law. Both types of deviations are actually present, as is apparent in the recordings of sound pressure levels made in an anechoic chamber by A. N. Rivin.[3]

Some of the measurements in our chamber were made at frequencies high enough and distances large enough to produce appreciable atmospheric-absorption effects. On this account we use as a model a reference sound field having an exponentially attenuated inverse square law for its rms sound pressure. The corresponding rms output voltage of the microphone is

$$V = Ae^{-\alpha(x-d)}/(x-d) , \qquad (1)$$

where A is a constant proportional to the source strength, α is the air attenuation coefficient for sound pressure amplitude, x is the distance between a convenient reference point on the source and a point on the microphone, and d is defined so that $x - d$ is the distance between the effective acoustic center of the source and the microphone. The formula (1) may be regarded as an approximation to the "true" sound field, with A, α, and d to be determined empirically from the experimental data. The procedure used to obtain these quantities is described in Section III.

A. N. Rivin[3] and F. Ingerslev *et al.*[4] used a method that avoids determination of A and d. The microphone output voltage is fed into a potentiometer that is mechanically coupled to the carriage supporting the microphone. The attenuation of the potentiometer is arranged to be inversely proportional to the distance between the microphone and sound source to counteract the effect of spherical spreading. To take care of the position of the acoustic center, additional attenuation is introduced in the microphone output circuit until, by trial and error, the deviations are centered approximately about a straight line over a range not too far from the source, where the deviations are small. The combined effects of reflections from the walls and the systematic variations mentioned above, including absorption of sound by the medium, appear as deviations from a constant value.

III. DEVIATIONS FROM INVERSE-SQUARE LAW—MEASUREMENTS AND RESULTS

Two types of inverse square law experiments were performed in the NBS anechoic chamber. In one experiment the source was held stationary near one end of the room and the receiver moved relative to the source. The paths traversed for this experiment are shown in Fig. 3. In the other case, both source and receiver were moved apart relative to the center of the room up to a separation of 6 m.

In Fig. 4(a), a summary of the sources and receivers used and an indication of their directional patterns are given for the measurements in which the source was held stationary. The loudspeaker and tuned pipes were suspended from the ceiling by 2.5-cm-diam rods; the ceramic sphere was supported at the end of a thin rod protruding from the wall. The microphones and preamplifiers were mounted on a cart constructed of a light framework of 2.7-mm-diam rod. Figure 5 shows two of the carts. The one at the right is supporting a 0.63-cm-diam microphone and preamplifier. The cart at the left holds an electrodynamic microphone used as a moving sound source. Two 2.4-mm-diam stranded wires, spaced parallel to each other, were stretched across the room along the traverse at the same height, with a lateral separation of about 15 cm. The carts were hung on these wires with the transducers located

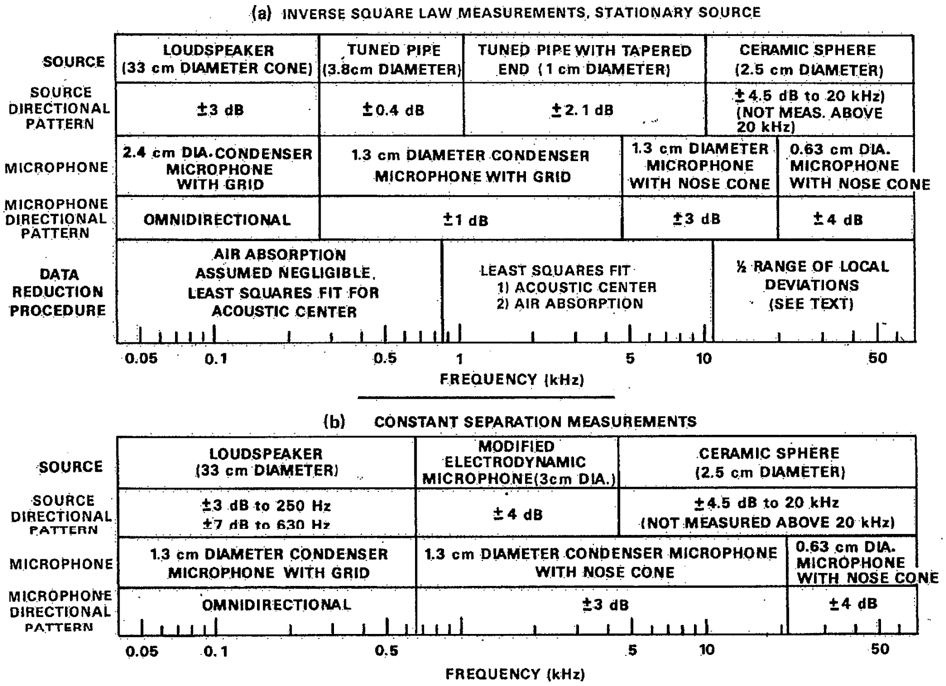

FIG. 4. Sources, microphones, directional characteristics, and data reduction procedures used. The loudspeaker was mounted in a closed, rectangular box with front-face dimensions of 35×63 cm and a depth of 29 cm.

30 cm below their centerline. As the cart supporting the microphone was pulled along the wires, measurements of the microphone rms output voltage were taken at approximately every centimeter. The microphone output voltage was fed through a tuned amplifier to an analog-to-digital converter. The signal-to-noise ratio of the amplifier output exceeded 30 dB at all times. The data were recorded on punched paper tape for subsequent analysis by a digital computer. At the same time, analog measurements were made on a sound level recorder to corroborate the digitized data and for analysis above 10 kHz.

The digitized data from 40 Hz to 10 kHz were processed by one of two methods, depending on the frequency.

A. 40–800 Hz

At these low frequencies it was assumed that the attenuation coefficient α was zero. Equation (1) can then be written as

$$1/V=(-d/A)+(1/A)x \ . \qquad (2)$$

The right-hand side is a first-degree polynomial in x with coefficients $-d/A$ and $1/A$. The coefficients were determined from a least squares curve-fitting procedure with the aid of a digital computer, using experimentally determined values of $1/V$ with x as the independent variable. The values of d and A were then calculated from the coefficients of the fit.

The physical interpretation of this procedure is as follows. A straight line is fitted to the experimental values of $1/V$ versus x and extended to cross the x axis. We consider the hypothetical case of the microphone approaching the effective acoustic center, that is, the center of spherical waves measured at large distances. Then $V\rightarrow\infty$ and, in the limit, $1/V=0$. At this point, $x=d$. Thus, d is the distance of the effective acoustic center from the reference point $x=0$.

Although data were taken from about 0.2 to 6 m from the source, the least-squares fits to determine A and d were made over a limited range of distances, ac-

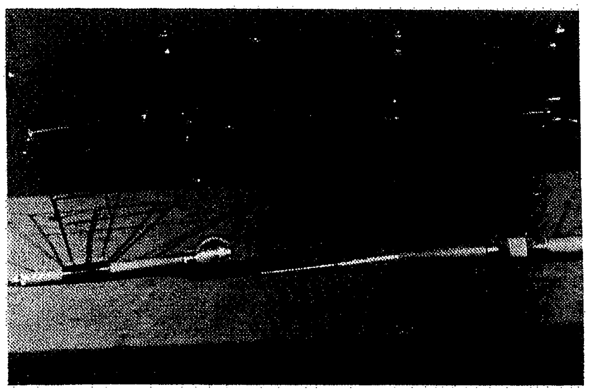

FIG. 5. Carts that carried the microphones and preamplifiers along the traverse. At the right, a 0.63-cm-diam microphone mounted on a 1.3-cm-diam preamplifier is shown. At the left is an electrodynamic microphone used as a moving sound source.

TABLE I. Range of fit for determination of A and d.

Frequency range (kHz)	Range (m)
0.04–0.25	0.5–1.0
0.315–0.63	0.2–1.5
0.80	0.5–1.5

cording to Table I. The considerations involving the systematic variations discussed in Section II and the reflections from the walls dictated the choice of these limited distances for determining A and d. With increasing distance between source and microphone, reflected waves from the chamber walls become more important relative to the direct wave, tending to decrease the accuracy with which A and d could be determined. Two or more different ranges of distances were used at each frequency in the least-squares curve-fitting procedure. It was found that the parameters were not sensitive to the range of the fit as long as measurements were not made too close or too far from the source.

Using the values of A and d thus determined, a voltage $V_f(x)$ was calculated from Eq. (2) for each data point from 0.5 to 6 m to establish a reference line extending out to 6 m. Deviations D from the inverse square law were then determined over this range from the expression

$$D = 20\log[V_e(x)/V_f(x)]\,, \tag{3}$$

where $V_e(x)$ is the microphone output voltage.

B. 1–10 kHz

The effects of atmospheric absorption from 1 to 10 kHz were taken into account by two successive curve fits. First, when $e^{\alpha d}$ is close to unity, we note that Eq. (1) can be written

$$e^{-\alpha x}/V \approx (-d/A) + (1/A)x\,. \tag{4}$$

Eq. (4) differs from Eq. (2) only by the factor $e^{\alpha x}$, which serves to linearize a curve that would otherwise have an increasing slope due to atmospheric absorption. Values of α were calculated at each frequency by the method of Evans and Bazely[5] and the measured values of V multiplied by the factor $e^{\alpha x}$ for each voltage measurement from 0.5 to 1.5 m. The same curve-fitting procedure was then used over this range to find d and A.

Next, for αd close to unity, we note that Eq. (1) can also be written

$$\ln[V(x-d)] \approx \ln A - \alpha x\,. \tag{5}$$

Using the value of d already obtained, the left-hand side of Eq. (5) was computed for each measurement point from 0.5 to 6 m. An analogous curve-fitting procedure was then carried out over the 0.5–6-m range to determine A and α. $V_f(x)$ was calculated from Eq. (1) over the entire range using values of d obtained from the first fit to Eq. (4) and values of A and α from the second fit to Eq. (5). Deviations were calculated, as before, from Eq. (3). (A method for determining all three of the coefficients with a single least-squares fit has also been used successfully from 20 to 100 kHz.[6])

The values of the parameters obtained from the least-squares fits were compared with theoretical values available in the literature. Ando[7] defined an acoustic center in terms of phase differences, which, for an unflanged thin-walled pipe, has the same values as the end corrections calculated previously by Levine and Schwinger.[8] The experimental and theoretical values for the pipe sources are compared from 0.315 to 10 kHz in Fig. 6, which also shows the measured values of the effective acoustic center distances d for the loudspeaker from 40 to 250 Hz. The maximum differences between the theoretical air-absorption coefficients obtained by Evans and Bazely's method and those obtained from anechoic chamber measurements were 0.05 dB/m up to 2.5 kHz and 0.17 dB/m up to 10 kHz.

C. 12.5–63 kHz

Above 10 kHz a spherical ceramic source was used to obtain sufficient omnidirectionality. However, since the sound output of this source was found to drift with time, it was necessary to resort to a third method for obtaining deviations from the inverse square law. Instead of using a least-squares procedure, the envelope of the curve of sound pressure level versus transducer separation was considered. Over small distances, but encompassing several local maxima and minima, it was assumed that the drift was relatively small and that the fluctuations of the output within the envelope were caused by room effects. One-half of the difference between the upper and lower contours of the envelope was taken to be the absolute value of the maximum deviation.

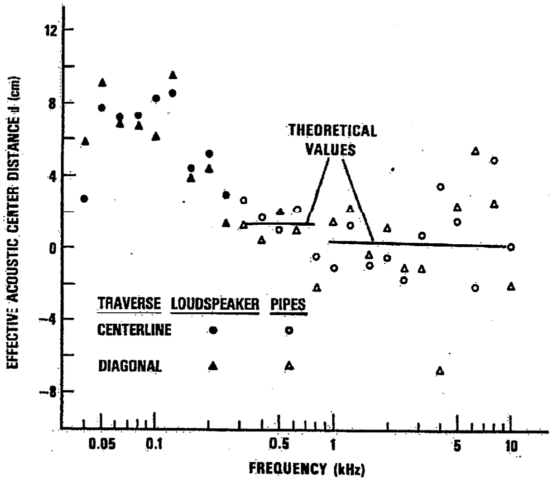

FIG. 6. Measured values of effective acoustic center distances d from 40 Hz to 10 kHz. For the loudspeaker, d was measured from the front face of the enclosure; for the pipes, d was measured from the open end. Theoretical values for acoustic centers (end corrections) of the pipes are shown for comparison (see text).

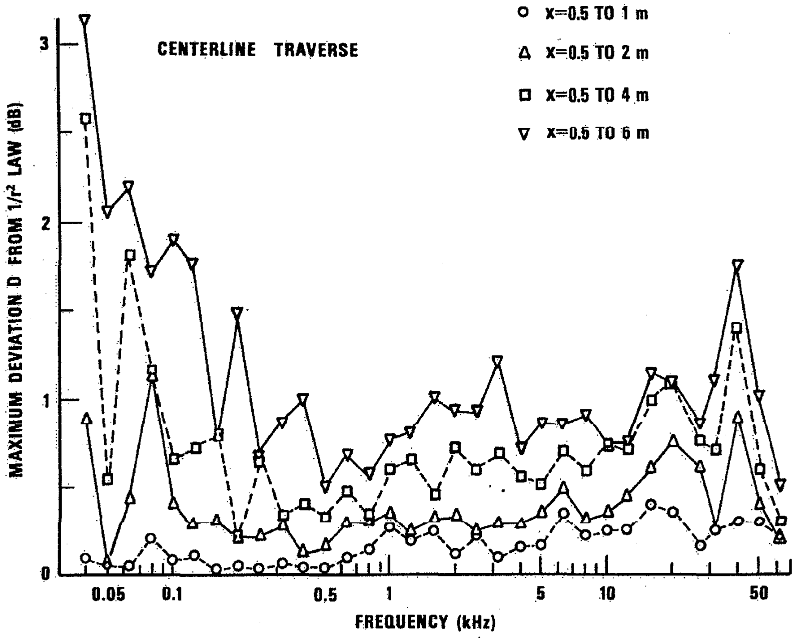

FIG. 7. Absolute values of maximum deviation from inverse square law for a stationary source and the centerline traverse shown in Fig. 3(a). The standard deviation of residuals from 1 to 10 kHz and from 0.5 to 6 m was approximately 0.4 dB.

The composite results of measurements from 40 Hz to 63 kHz for the centerline and diagonal traverses are shown in Figs. 7 and 8, respectively. The absolute values of the maximum deviations from the inverse square law are plotted as a function of frequency with the range of separation as the parameter. The Helmholtz resonator absorption effect described in Ref. 1 shows up as a dip in the curves at either 50 or 63 Hz. Aside from this, the general trend of the curves is downward with frequency until about 500 Hz, above which a gradual increase occurs.

From 1 to 10 kHz, the standard deviations of the residuals were also calculated for the range 0.5 to 6.0 m. For the centerline traverse, the smallest standard deviation was 0.38 dB at 10 kHz and the largest 0.49 dB at 1.25 kHz. For the diagonal traverse, the extreme values of the standard deviations were 0.36 dB

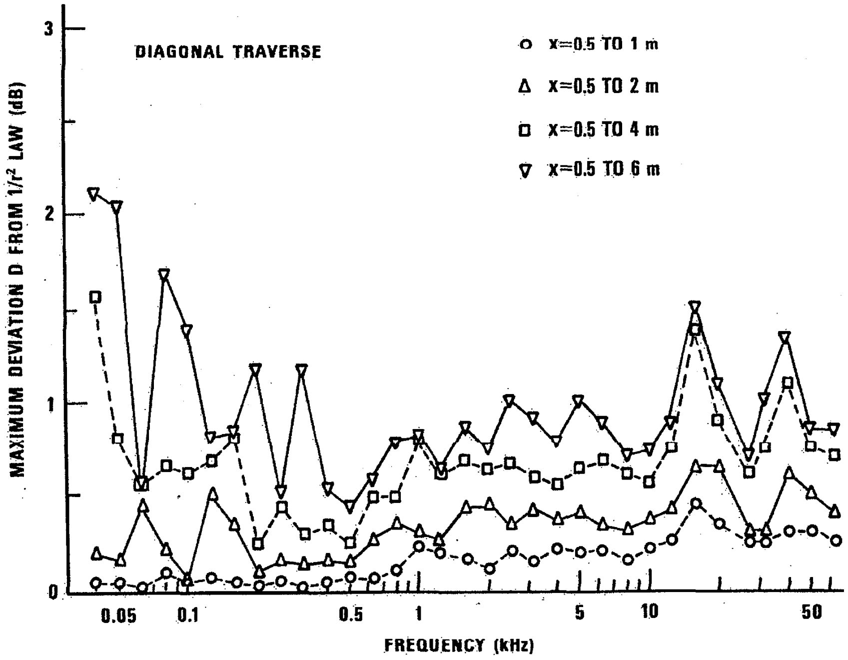

FIG. 8. Absolute values of maximum deviation from inverse square law for a stationary source and the diagonal traverse shown in *Fig.* 3(b). The standard deviation of residuals from 1 to 10 kHz and from 0.5 to 6 m was approximately 0.4 dB.

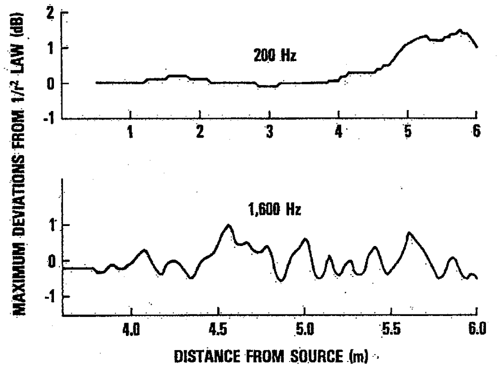

FIG. 9. Sample individual deviations at 200 and 1600 Hz as a function of distance from the source for the centerline traverse shown in Fig. 3(a).

at 10 kHz and 0.46 dB at 5 kHz. Thus, the standard deviations for the range 0.5–6 m are approximately half of the maximum deviations for the same range.

Sample plots of the individual deviations from the inverse square law at 200 and 1600 Hz, calculated point by point from Eq. (3), are shown in Fig. 9. These plots are for the centerline traverse of Fig. 3(a) and cover the distances shown in Fig. 9. The individual points on the curves were obtained from the same computer output data used to plot the 200- and 1600-Hz points in Fig. 7. The points have been connected for clarity.

A qualitative comparison between the inverse square law measurements and measurements made in a plane-wave tube[1] on a single wedge of the same length, but 20×20-cm base, is shown in Fig. 10. One-half of the standing wave ratios measured in the plane-wave tube are compared with the maximum deviations in the anechoic chamber for the range 0.5–4 m. With the exception of a few points, there is fairly good similarity in the shapes of the curves. Thus, it seems that measurements taken in a plane-wave tube prior to the construction of an anechoic chamber can be of some help in predicting the performance of a completed chamber at low frequencies.

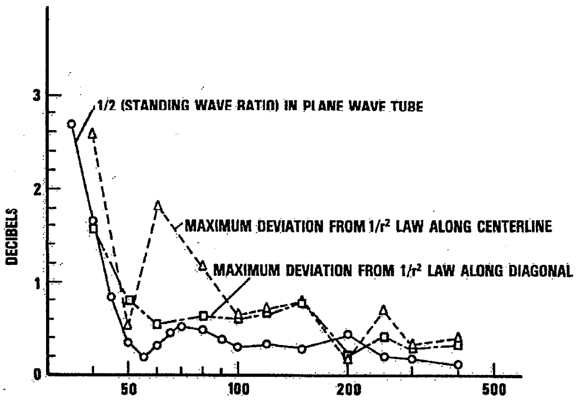

FIG. 10. Comparison between one-half of the standing wave ratios measured for a 20×20-cm wedge in a plane-wave tube and maximum deviations from the inverse square law in the anechoic chamber from 0.5 to 4 m.

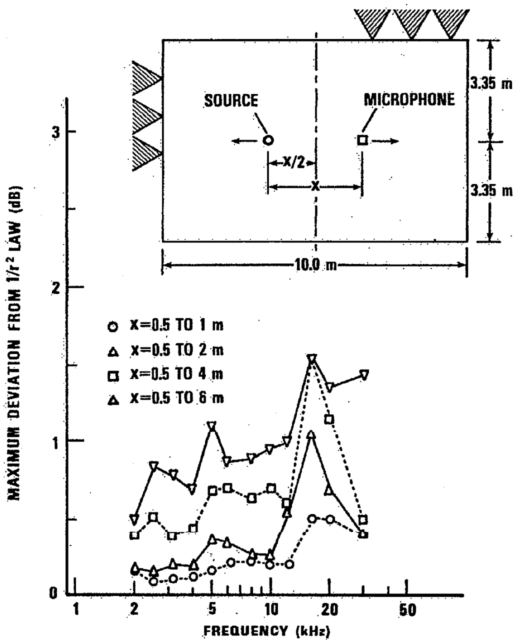

FIG. 11. Absolute values of maximum deviation from inverse square law for source and microphone moving away from each other along the centerline traverse. The transducers traveled apart at the same speed and remained centered with respect to the midpoint of the room.

Inverse square law experiments were also performed with both the source and microphone moving apart over the frequency range 2–30 kHz. At 2, 3.15, and 4 kHz, an electrodynamic microphone, modified to simulate a 3-cm-diam piston set in a 4.8-cm-diam sphere,[9] was used as a source. From 5 through 30 kHz, the ceramic sphere was used. The sources and microphones were mounted on carts of the same kind as described at the beginning of this section and were drawn apart simultaneously relative to the center of the room. The results along the centerline traverse are shown in Fig. 11. The maximum deviations are not substantially different than those for a stationary source, indicating that over the frequency range 2–30 kHz, errors in sound pressure measurement with sources and microphones centered in the room would be similar to those for a source location 1.6 m from one end of the room, as illustrated in Fig. 3.

In applying the results given in Figs. 7, 8, and 11 to sound measurements made in the anechoic chamber, it should be noted that the values of measured deviations depend, in general, not only on room reflections and the locations of the transducers, but also on the directional characteristics of the transducers. These observations lead to the conclusion that in the use of an anechoic chamber, inverse square law measurements

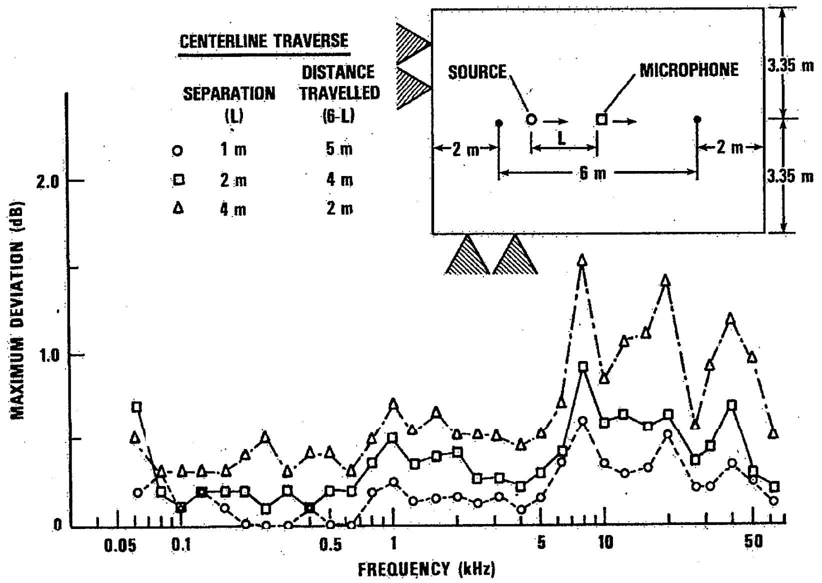

FIG. 12. Absolute values of maximum deviation from average sound pressure level along centerline traverse. Source and receiver were moved together in the same direction at a constant separation *L*.

should be made with the particular source and microphone to be used. The source should be located where it would be for the measurements, and the microphone moved away from the source along a line passing through the effective acoustic center of the source.

IV. CONSTANT SEPARATION MEASUREMENTS

Another method for studying the acoustical properties of anechoic chambers consists of measuring the changes in rms sound pressure as the source and microphone are drawn simultaneously across the room at a fixed separation. Bell *et al.*[10] made frequency response measurements of a source in different parts of the room at a fixed separation, but in our experiments position was changed continuously, with frequency as the parameter. The advantages of the constant separation method are that (1) neither acoustic center nor air absorption values need be known and (2) diffraction and scattering from the apparatus that supports the

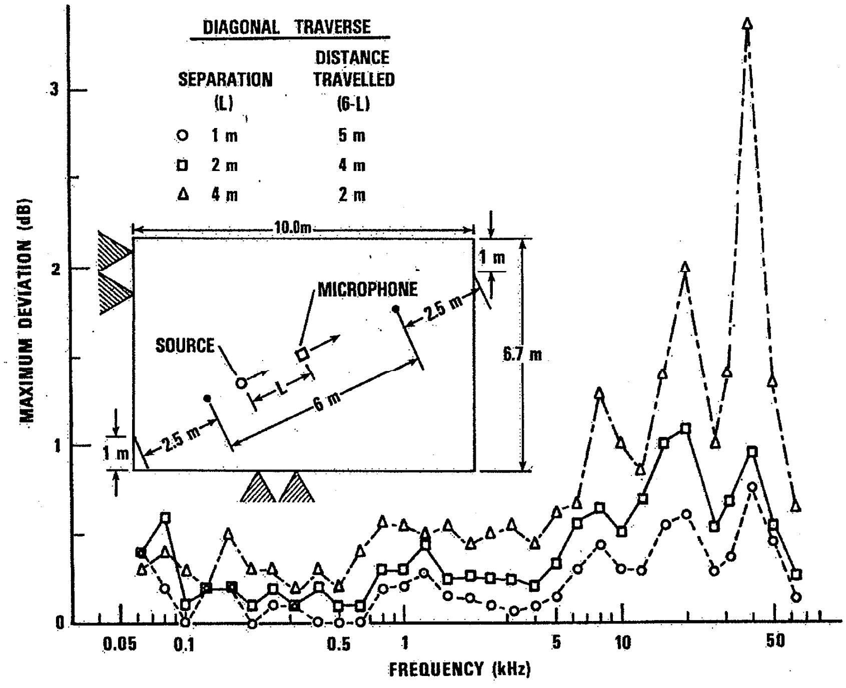

FIG. 13. Absolute values of maximum deviation from average sound pressure level along diagonal traverse lying in a horizontal plane midway between the tips of the floor and ceiling wedges. Source and receiver were moved together in the same direction at a constant separation *L*.

transducers are of secondary importance, since they do not change for a given separation. The disadvantage of the method is that it does not, in contrast to inverse square law measurements, predict the error in sound pressure measurement that would occur for specified locations of sources and receivers. However, it does provide information on the differences in sound pressure that one would expect at different locations in the room for a given separation of an omnidirectional source and microphone.

The characteristics of the transducers used in the measurements are shown in Fig. 4(b). Because of the difficulty of traversing with tuned pipes, the modified electrodynamic microphone described in Sec. III was used as a source from 800 Hz to 4 kHz.[9] With the exception of the loudspeaker, which was mounted on a wagon that rolled on tracks laid across the anechoic chamber wire mesh floor, the sources and microphones were supported by the carts described in Sec. III. The carts were connected by a thin wire so that when either the source or microphone was pulled along, the wire became taut and kept the distance between the transducers constant.

Data for the constant separation measurements were taken along the same traverses used in the inverse square law measurements and deviations measured from the average value of the sound pressure level over the traverse. Each centerline run started with the source about 2 m from the wedge tips at one end of the room and ended with the microphone about 2 m from the wedge tips at the other end. For the diagonal runs, the closest perpendicular distance of the transducers to the wedge tips was approximately 2.1 m. In each case the sum of the distance that the coupled cart system was moved and the separation of the carts was 6 m.

Figures 12 and 13 show the results of the measurements taken along the centerline and diagonal traverses, respectively. At low frequencies, the constant-separation method yields substantially smaller maximum deviations than those from the inverse square law because the wavelengths are too long for this kind of experiment. This low-frequency comparison emphasizes the necessity for inverse square law measurements in estimating the accuracy of sound pressure measurements in an anechoic chamber. The maximum deviations increase somewhat with frequency, with prominent peaks in the curves occuring at 8, 20, and 40 kHz for the 4-m separation.

The large deviations at these three frequencies, which occurred frequently along the entire lengths of the traverses, are believed to have been caused by the wire-mesh floor. Tone-burst measurements made subsequently showed clear reflections from the floor in the range of 4–40 kHz, but the results were difficult to assess quantitatively, partly because of irregularities in the appearance of the tone bursts on the oscilloscope screen and partly because of the complexity of the theoretical problem. The magnitude of the tone-burst reflections increased with frequency, although not monotonically.

At 40 kHz, with a 4-m separation and along the diagonal traverse, the maximum deviation was 3.4 dB. This relatively large deviation, which was repeatable and which was smaller along the centerline traverse and in both sets of inverse square law measurements, stresses the fact that anomalies in room behavior that are a strong function of transducer position can be easily missed when only discrete sets of positions are used.

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