ULTRASONIC ANECHOIC CHAMBER QUALIFICATION: ACCOUNTING FOR ATMOSPHERIC ABSORPTION AND TRANSDUCER DIRECTIVITY

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ABSTRACT

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Qualifying an anechoic chamber for frequencies that extend into the ultrasonic range is necessary for research work involving airborne ultrasonic sound. For example, an anechoic chamber allows for measurements of the direct sound radiated by an object without reflections from walls. The ANSI S12.55/ISO 3745 standard which covers anechoic chamber qualification does not extend into the ultrasonic frequency range, nor have issues pertinent to this frequency range been fully discussed in the literature. An increasing number of technologies are employing ultrasound; hence the need to develop facilities to conduct basic research studies on airborne ultrasound. This thesis will specifically discuss the need to account for atmospheric absorption and issues pertaining to source transducer directivity by presenting some results for qualification of a chamber at Brigham Young University. [This work has been funded by the Los Alamos National Laboratory]

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I. Introduction

Anechoic chambers are essential for the free-field measurement of sound. The types of materials used, the shapes of the material and the construction of anechoic chambers has been studied by Bedell,[1] Beranek and Sleeper,[2] and Hardy *et al.*[3] to recreate the free field environment. As technology advances and research in acoustics encompasses more ultrasonic applications, it becomes necessary to understand the capacity for an anechoic chamber to produce a free field environment for ultrasonic sources. This thesis addresses the issues that arise when qualifying an anechoic chamber for ultrasonic frequencies.

ANSI S12.55/ISO 3745[4] is the current standard for qualifying anechoic chambers. It specifies techniques and procedures that are used to properly qualify anechoic chambers. Restrictions and deviations from the inverse square law of an omnidirectional source are provided. Unfortunately, these deviations are only specified for >6.3 kHz but the standard makes no attempt to address frequencies above 20 kHz. It is becoming more important to standardize the qualification process for frequencies in the ultrasonic range. Before the standard was created, anechoic chamber qualifications crossed into the ultrasonic frequency range, though the ultrasonic range was not typically the focus of these works. As an example Hardy *et al.* tested the anechoic room at the Parmly Sound Laboratory up to 24,000 Hz but did not discuss the region above 20 kHz in detail.[3]

Further research has been conducted to verify the quality of the procedures in the ANSI S12.55/ISO 3745 standard. It has been shown by Cunefare *et al.*[5] and Luykx and Vercammen[6] that a continuous traverse method for qualifying anechoic chambers is preferred and more accurate over the discrete measurements allowed by the standard. In addition, Cunefare and Badertscher,[7] as well as, Wittstock and Bethke[8] show the importance of pure tone measurements compared to broadband measurements, due to inherent averaging that takes place to obtain broadband noise levels, which subsequently suppresses interference, and therefore the deviation from the inverse square law, in an anechoic chamber qualification.[7] However, the earlier work by Cunefare *et al.* asserts that the use of broadband noise may be tolerable if those are the types of signals commonly employed in the anechoic chamber to be qualified.[5] In this thesis, one third octave band levels with random noise signals are employed. The purpose of this thesis is to illustrate the issues pertinent to chamber qualification at ultrasonic frequencies and the use of a continuous traverse and pure tones in the ultrasonic frequency range is suggested as future work.

In addition to the standard practices of qualifying an anechoic chamber[4-5,7] it is important to note that atmospheric absorption becomes an important factor as the frequency becomes large, as Koidan and Hruska[9] suggested in their qualification measurements up to 63 kHz. However, Koidan and Hruska's work did not address the implications of not accounting for atmospheric absorption in the so called fixed reference and optimal reference methods used for qualifications.

The ANSI S12.55/ISO 3745 standard does address the need for omnidirectional sources in chamber qualifications, but due to the inherent nature of common ultrasonic sources, it is not currently possible to acquire ultrasonic sources with the directivity properties required by the standard. Koidan and Hruska stated that they used an omnidirectional ultrasonic source in their work but provided no details to confirm that this was indeed the case.[9]

The purpose of this thesis is to address the impact of atmospheric absorption on the different types of reference methods for the calculation of deviations from the inverse square law, and to directly address the issues related to the very high directivities commonly found in airborne ultrasonic sources. Qualification measurements from the 6.3 kHz third octave band through the 80 kHz third octave band and up to 100 kHz (not including the full 100 kHz third octave band) are conducted to illustrate these issues. By doing such qualifications, the importance of atmospheric absorption becomes apparent, as well as the issues with ultrasonic transducer directivity.

II. Experiment Setup

The anechoic chamber under consideration in located on the campus of Brigham Young University and has working dimensions of 3.57 x 2.88 x 2.59 m. The anechoic wedges are made of open cell foam and are created by Future Foam (part number 70200YW13) with a 0.032 g/cm^3 (2 lbs/ft^3) and cut into wedges with the dimensions given in Fig. 1. These foam wedges have a base that is 30.48 cm^2 and are alternately oriented as is commonly done in anechoic chambers.

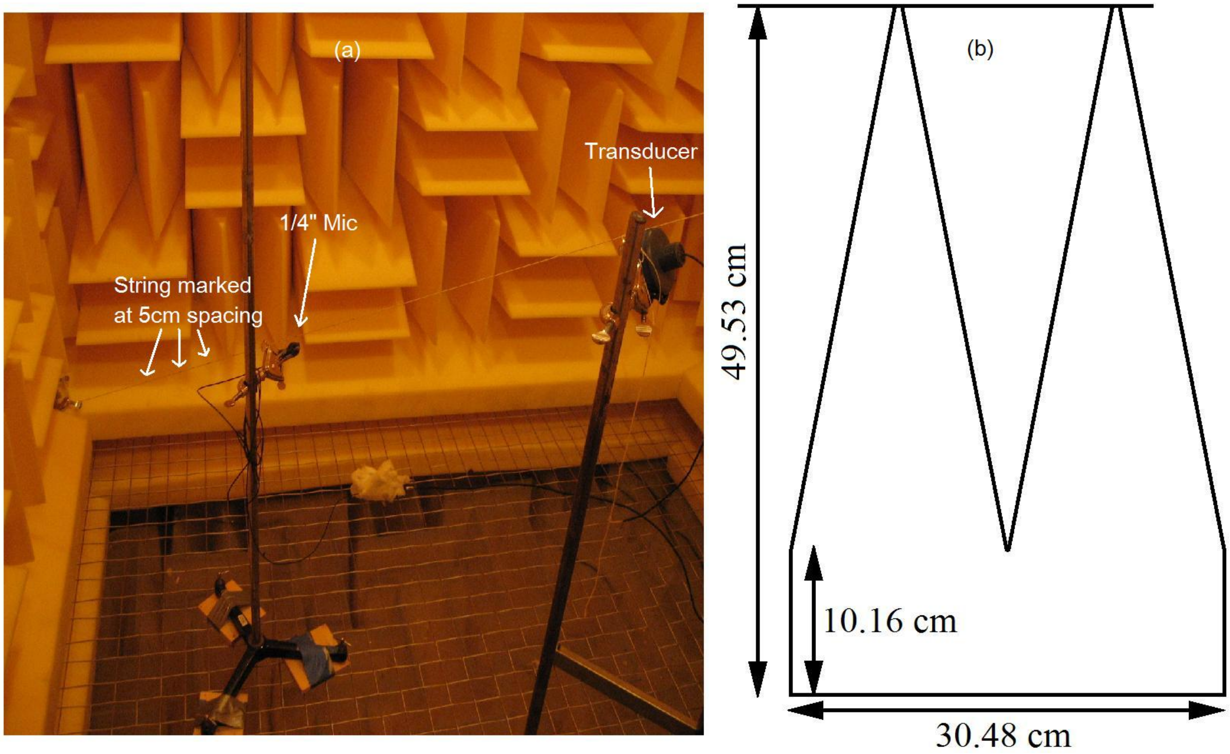

FIG. 1. (a) Photograph of the chamber in which the qualification measurements were conducted for this thesis. (b) Schematic drawing of the wedges constructed for this chamber.

Measurements are made with two Hewlett Packard 35670A Dynamic Signal Analyzers (one is a 2-channel analyzer and the other is a 4-channel analyzer) using swept sine or random noise as the excitation signal depending on the frequency band under test. The 4-channel analyzer possesses swept sine measurement capabilities up to a frequency of 51.2 kHz. The 2-channel analyzer could span a frequency range up to 102.4 kHz but did not possess the swept sine option. Thus, for bands 50 kHz and above, the 2-channel analyzer is used with random noise excitation and power spectra are determined. For the bands below 50 kHz, a swept sine excitation is used and transfer functions are determined. The specifics of the measurements conducted for each third octave band frequency range are specified in Table 1. The averaging procedure specified in Eq. (1) is carried out whether swept sine or random noise signals are used. Swept sine transfer function data is preferred to broadband, random noise power spectrum data, due to the high degree of available signal to noise ratio.

For each given set of microphone recordings along a corner to corner traverse, measurements are made with a G.R.A.S. 6.35 mm (1/4 in.) 40 BE free-field, prepolarized microphone with a G.R.A.S. 26CB preamplifier, placed 0.5 m from the source to stay outside of the near field of the source. An effort was made to maintain at least 10 dB of signal to noise for all measurements, as required by the standard. The sources used are a KEF Audio Hypertweeter, and the following transducer model numbers from Parasonics Corp.: 4012A, PAR58T, and 7516. The source is placed in the approximate center of the room and measurements are made at 5.0 cm spaced intervals from 0.500 m up to 1.000 m away from the source using a taut string marked at the positions to be measured. The measurement traverses are made directly into various corners as specified by the standard.[4] However this procedure differed from the standard by aiming the source towards the corner being measured, because of the sources' high directionality. The microphone diaphragm then faced the source. This process is repeated 5 times for different corners of the chamber. This method is admittedly not a rigorous qualification of an anechoic chamber as the spacing between microphone positions is 7.3 wavelengths apart at 50 kHz. The continuous traverse method, where measurements should be made every 0.15 of a wavelength and with the microphone being moved at controlled speeds[5] may not be practical for ultrasonic frequencies as measurements would need to be made every 1.03 mm for a frequency of 50 kHz for example. Further work on ultrasonic chamber qualification should address the issue of microphone spacing and the tolerable speeds at which the microphone may be moved.

Once these measurements are completed, the data is then post processed with MATLAB. For each measurement location, x , the third octave band level, $L_{1/3}(x)$, is determined,

$$L_{1/3}(x) = \frac{1}{N} \sum_{n=f_l}^{f_u} p^2(x,n), \tag{1}$$

where N is the number of frequency bins in the band (at least 100 bins are used for each band), f_l is the lower frequency limit for the frequency band, f_u is the upper frequency limit for the frequency band, p is the time-averaged pressure at the measurement location, and n is an individual frequency bin. $L_{1/3}(x)$ is then compared to the expected spherical spreading levels. In strict accordance with the standard, a divergence of ±1.5dB in $L_{1/3}(x)$ from spherical spreading levels is allowed for frequencies of 6.3 kHz or more.[4] Air absorption, not covered by the standard, is accounted for[10-11] prior to averaging the pressures using temperature and humidity information provided by an Oregon Scientific weather station, model BAR388HGA.

Table 1. The measurements, and measurement types used, including the sources used and the third octave bands up to the highest frequency measured. Measurements for the 100 kHz band only spanned 90-100 kHz in this work due to equipment limitations.

Center frequency (kHz)	Lower limit (kHz)	Upper limit (kHz)	Source	Signal type	Measurement type
6.3	5.6	7.1	Hypertweeter	Swept sine	Transfer function
8	7.1	9	Hypertweeter	Swept sine	Transfer function
10	9	11.2	Hypertweeter	Swept sine	Transfer function
12.5	11.2	14	Hypertweeter	Swept sine	Transfer function
16	14	18	Hypertweeter	Swept sine	Transfer function
20	18	22.4	Hypertweeter	Swept sine	Transfer function
25	22.4	28	Hypertweeter	Swept sine	Transfer function
31.5	28	35.5	Hypertweeter	Swept sine	Transfer function
40	35.5	45	40kHz Piezoelectric	Swept sine	Transfer function
50	45	56	40kHz Piezoelectric	Random Noise	Power Spectrum
63	56	71	58kHz Piezoelectric	Random Noise	Power Spectrum
80	71	90	75kHz Piezoelectric	Random Noise	Power Spectrum
100	90	112	75kHz Piezoelectric	Random Noise	Power Spectrum

III. Results

This section will address a few issues that arise for ultrasonic anechoic chamber qualification. Perhaps an obvious issue is that atmospheric absorption must be accounted for, but how this affects the optimal and fixed reference methods is important to understand. The next issue is that of the directivity of the transducers. The high directivity of the source likely does not illuminate the entire chamber and thereby can be considered to provide a pseudo qualification for an anechoic chamber.

III. A. Atmospheric Absorption

As Koidan and Hruska discovered, at ultrasonic frequencies it becomes clearer that atmospheric absorption is an issue. Shorter wavelengths and larger distances provide increasing divergence from theoretical predictions for pressure by spherical spreading due to atmospheric absorption as seen in Fig. 2. Also the standard only specifies a divergence from 1/r theory below 630 Hz, frequencies between 800 Hz and 5000 Hz, and then for frequencies above 6300 Hz for an anechoic room. It is not likely that the standard intended for this last allowable deviation to apply to the ultrasonic frequency range.

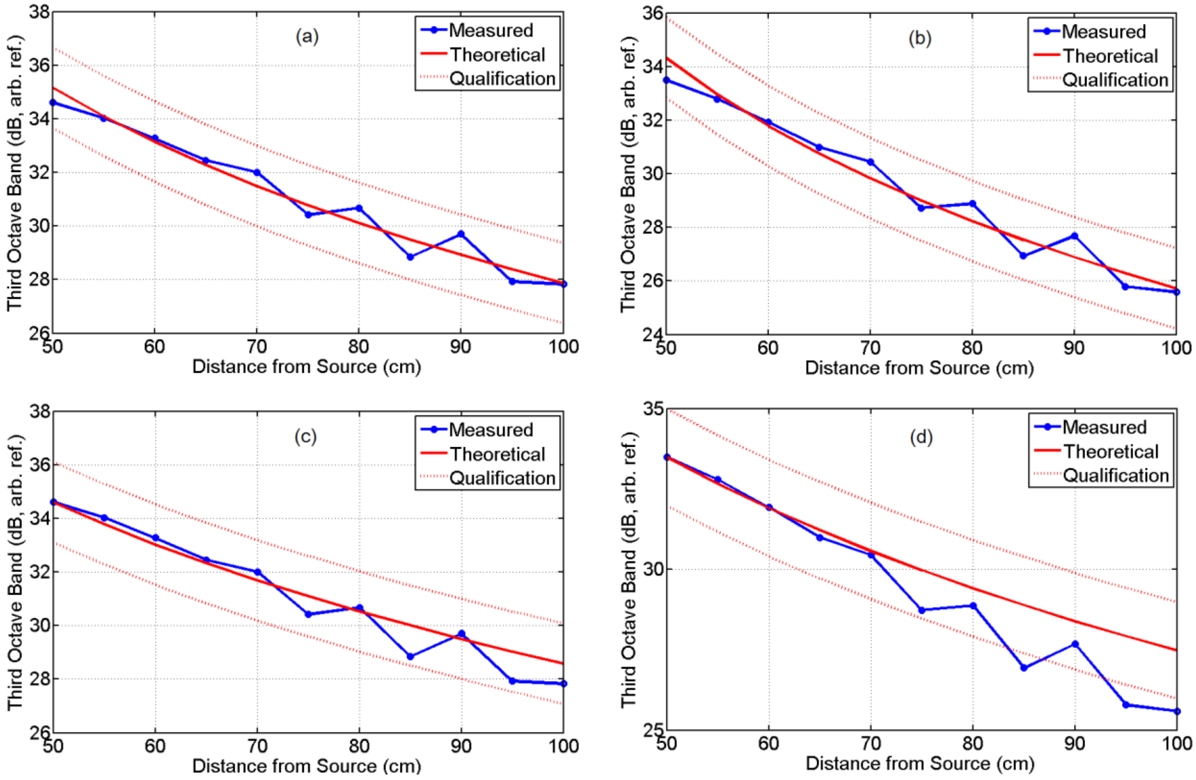

FIG. 2. Qualification measurements compared to spherical spreading with the allowable deviation lines indicated. (a) Accounting for air absorption using the optimal reference method (r_o=13.7 cm correction). (b) Without accounting for air absorption using the optimal reference method. (r_o=20.6 cm correction) (c) Accounting for air absorption using the fixed reference method at 0.5m. (d) Without accounting for air absorption using the fixed reference method at 0.5m.

Two methods have been proposed by others when fitting data to the 1/r spherical spreading curve expected of pressure in a free field environment. The first is the fixed reference method (FRM).[2-3,12-14] A microphone is placed at a reference distance and the theoretical sound pressure is given by equation (2)

$$L_p(r_i) = L_p(r_{ref}) - 20\log_{10}\left(\frac{r_i}{r_{ref}}\right), \qquad (2)$$

where $L_p(r_i)$ is the sound pressure level at r_i, $L_p(r_{ref})$ is the sound pressure at r_{ref}. Equation (2) provides the theoretical curve fit for the data.[5] The optimal reference (ORM) method[5] provides a fit based on the apparent strength of the source a and r_0, the apparent offset between the measured source location and its effective acoustic center given by,

$$L_p(r_i) = 20\log_{10}\left(\frac{a}{r_i - r_0}\right), \tag{3}$$

where

$$a = \frac{\left(\sum_{i=1}^{N} r_i\right)^2 - N\sum_{i=1}^{N} r_i^2}{\sum_{i=1}^{N} r_i \sum_{i=1}^{N} q_i - N\sum_{i=1}^{N} r_i q_i}, \tag{4}$$

and

$$q_i = 10^{-0.05 L_{p_i}}, \tag{5}$$

where L_{p_i} is the sound pressure level at r_i. N is the number of measurement points along the traverse and r_i is the same as in Eq. (2). This provides another fit for the 1/r curve to the data as seen in Figs. 2(a) and 2(b). In each of these cases the ORM suggests that the traverse is anechoic over its span.

Figures 2(c) and (d) show how air absorption must be accounted for as frequencies increase, especially for qualifications that extend over large distances, using the FRM. As the distance increases considerably, ultrasonic qualifications will fall outside of the allowable deviations without atmospheric absorption accounted for. The FRM only qualifies when absorption is accounted for.

Unfortunately, the ORM does not seem to provide an accurate effective acoustic center for ultrasonic sources as, in the case shown in Figs. 2(a) and 2(b), where the ORM estimated r_0 as 13.7 cm and 20.6 cm for the cases of with and without accounting for absorption, respectively. It is the author’s opinion that these estimates are clearly not accurate as the acoustic center cannot be located that far away from the physical surface of the transducer. In fact it is often the case that the ORM provides an unreasonable correction for the true source at ultrasonic frequencies. This correction is compounded when atmospheric absorption is applied. The FRM is preferred as it shows the data plainly, despite its inability to account for the acoustic center. Perhaps the FRM may be improved upon by allowing a user determined offset to be added to allow the data to best fit within the upper and lower bands and thereby providing a means to correct for an offset acoustic center, albeit in a somewhat arbitrary fashion. The ORM may be useful for lower frequencies (the audio band), but it provides an unrealistic estimate for the correction r_o for ultrasonic frequencies.

III. B. Transducer Directivity

Ultrasonic sources that comply with the directivity requirements of the ANSI S12.55/ISO 3745 standard are hard to find.[4] For an anechoic room, the standard specifies ±1.5 dB deviation in directionality for one-third-octave band frequency 630 Hz, ±2.0 dB for 800 to 5,000 Hz, ±2.5 dB for 6,300 to 10,000 Hz and ±5.0 dB for >10,000 Hz. At 6.3 kHz the Hypertweeter has a *ka* value of 0.73, while the 75 kHz ultrasonic transducer has a *ka* value of 33.7 at a frequency of 80 kHz. Thus due to the high *ka* values, one would expect high directionality over the majority of the frequency range for these qualification measurements. In addition to the high directionality, these sources have a relatively narrow frequency response. Due to the directionality of these sources, the source is pointed towards each measurement traverse to ensure a signal to noise ratio of at least 10 dB (as required by the standard[4]).

In an attempt to produce a more omnidirectional signal from the source, a beam blocker is constructed. The beam blocker consists of washers placed 3-4 cm from the source in an effort to break up the main beam at normal incidence. Figure 3(a) displays a photograph of the beam blocker placed in front of the 58 kHz ultrasonic source. Directivity measurements are conducted to determine its effect on the directivity. These measurements are made by placing the source on an Outline ET2 turn table and recording at 2.5 degree rotations for 360 degrees. The directivity measurements, with and without the beam blocker in place, are shown in Fig. 3(b) when a 63 kHz sine wave is emitted from the 58 kHz source. Note that the beam blocker, while not providing a smooth omnidirectional pattern that meets the standard's allowable limits, does make the directivity of the source more closely approximate that of an omnidirectional source than without the beam blocker in place, thereby illuminating more of the chamber's surfaces to allow for more reflections to take place. Average deviations from omnidirectionality are 22.5 dB (72.2 dB at most) without the beam blocker, while the deviations reduce to an average of 10.6 dB (38.2 dB at most).

Qualification measurements, for the 63 kHz band and higher, commonly yield levels that exceed the allowable ±1.5 dB range with the beam blocker in place. Though the 50 kHz band does stay within the allowable deviations with the beam blocker in place over each full traverse, there are a couple frequencies bins out of the 201 total bins that fall below the requirement for 10 dB of signal to noise ratio.

Figures 3(c) and 3(d) show examples of qualification measurements along one traverse without and with the beam blocker in place, respectively. Note that there appears to be evidence of interference from x = 70 cm and in the up and down swings in the data, though it is uncertain what degree of interference is present with the coarse spacing of microphone positions used.

Note that at 63 kHz, there are 9.2 wavelengths between measurement locations. A finer density of measurements locations for the microphone may yield larger deviations for this frequency band, but this will need to be the subject of future work. However, despite the coarse spacing of measurement locations, the general effect of modifying source directivity through the use of a beam blocker is evident from these examples.

The use of beam blockers is desirable to qualify an ultrasonic anechoic chamber for sources of unknown directional characteristics. However, there still may be a use for qualification measurements with directional sources. In the first paper by Cunefare *et al.* they stated that perhaps broadband noise levels are allowable for chamber qualification if only broadband measurements are to be made in the chamber under test. In a similar vein, we propose here that if the sources to be used in the chamber are strictly going to be directional then perhaps chamber qualification using these directional sources is tolerable (as long as this is understood when reporting data).

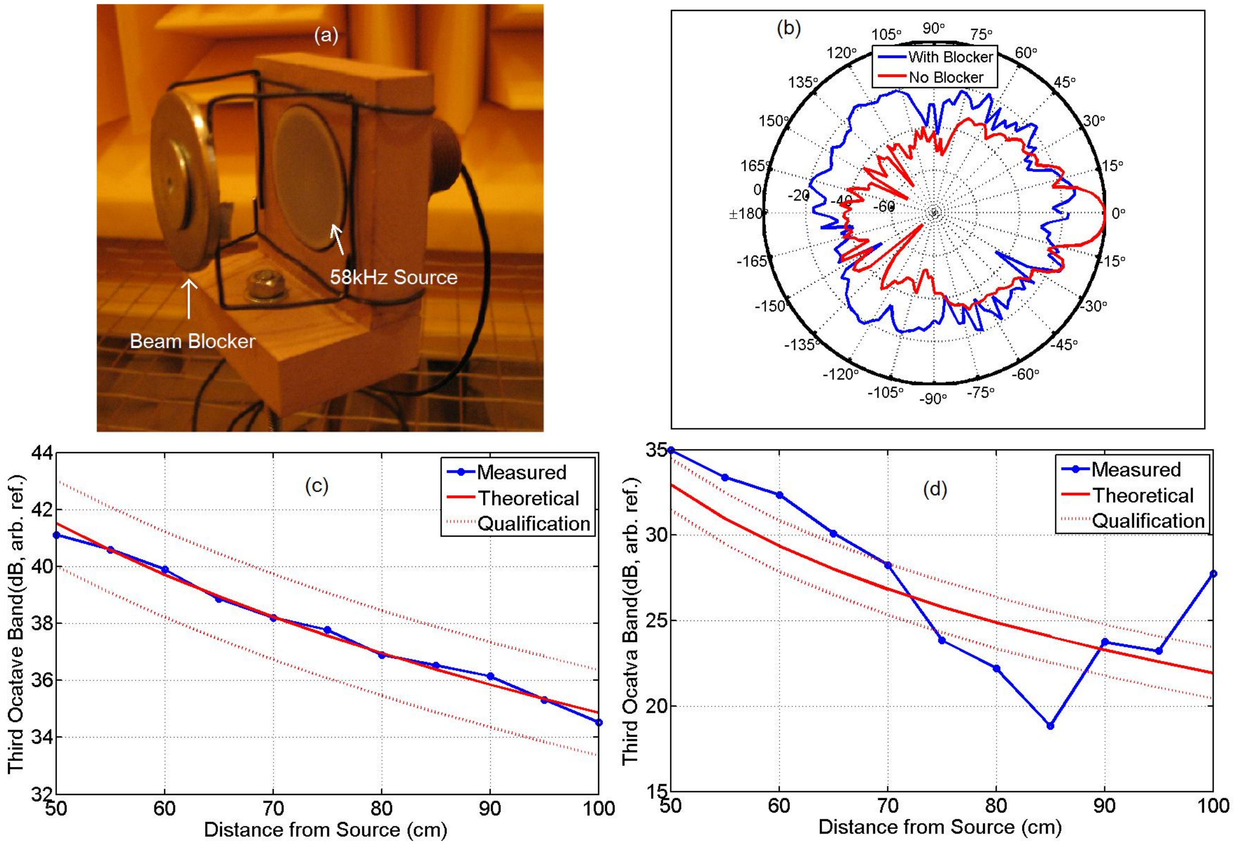

FIG. 3. (a) Photograph of the 58 kHz transducer with the beam blocker in place. (b) Directivity of the 58 kHz transducer, with and without the beam blocker displayed in dB relative to the maximum value at normal incidence for the transducer without the beam blocker. (c) Qualification measurement for the 63 kHz band without beam blocker. (d) Qualification for the 63 kHz band with the beam blocker.

IV. Conclusion

In the ultrasonic frequency range, anechoic chamber qualification requires that atmospheric absorption be accounted for even for distances of only 1 meter. When atmospheric absorption is not accounted for, the optimal reference method employs nonphysical estimates of the acoustic center of the source in order to provide a spherical spreading fit to the data. Even when absorption is accounted for, the optimal reference method yield nonphysical estimates for the acoustic center. Therefore, care must be taken when using the optimal reference method to ensure that the estimate of the source's acoustic center is physically legitimate. We propose that the fixed reference method be used for ultrasonic frequencies to avoid this issue.

Transducers used as sources for chamber qualification generally are highly directional. We propose that the source be aimed at each qualification traverse unless the source is sufficiently omnidirectional. Beam blockers are an effective way of decreasing directionality although more research is needed to design an optimal beam blocker. If directional sources used for qualification measurements, then perhaps they may be considered to be sufficient for measurements in the chamber that only utilizes sources of a similar degree of directivity.

Future work on ultrasonic chamber qualification may focus on determination of allowable specifications for measurement position spacings for a microphone along each traverse and the speed at which the microphone may be moved for continuous traverse methods. Future work may also explore ultrasonic chamber qualifications for pure tone levels versus third octave band levels.

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