Effect of boundary diffusers in a reverberation chamber: Standardized diffuse field quantifiers[a]

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The sound field inside a reverberation chamber must have a high degree of diffusivity to allow for the accurate measurement of various acoustic quantities. Typically, hanging or rotating diffuser panels are installed in the chamber in an effort to achieve this diffusivity. However, both of these diffuser types have certain limitations, and adequate sound field diffusivity is often difficult to realize. A 1:5 scale reverberation chamber has been used to systematically analyze the relative effectiveness of hanging diffusers versus an alternative diffuser type referred to as a boundary diffuser. To characterize sound field diffusivity, three quantifiers from the ASTM E90, ASTM C423, and ISO 354 standards have been used: maximum absorption coefficient, standard deviation of decay rate, and total confidence interval. Analysis of the quantifier data reveals that boundary diffusers and hanging diffusers produce roughly equivalent diffusion in the sound field. The data also show that the standards have certain inconsistencies that can obfuscate the characterization of sound field diffusivity, which may explain reproducibility and repeatability issues previously documented in the literature. *© 2014 Acoustical Society of America*.
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I. INTRODUCTION

This paper presents an investigation on the effect of different diffuser types on sound field diffusivity in a reverberation chamber as characterized by standardized quantifiers. Reverberation chamber diffusivity is of paramount importance when measuring several quantities used in architectural acoustics. Therefore, understanding the effect of diffusers in these chambers is imperative for accurately and precisely measuring these quantities. This work is the first to systematically compare two common diffuser types: hanging and boundary diffusers, and will provide clarity on their relative effectiveness in producing adequate diffusivity. Since reverberation chambers are used almost exclusively for standardized measurements, the critical analysis of the data and the discussion given in this paper are contextualized in relation to the chamber qualification procedures prescribed in these standards.

Reverberation chambers are used to measure acoustical quantities such as absorption coefficient, scattering coefficient, sound power level, and several others. These measurements require that the chamber possess a highly reverberant sound field, which is generally realized through a large chamber volume and through the use of massive boundaries (e.g., concrete) and highly sound-reflecting surfaces. Accurate measurements in the chamber also require a highly diffuse sound field, which is often achieved by design schemes such as non-rectangular geometry,[1] room dimensions whose ratios are not small whole numbers, and the addition of stationary or rotating diffusers within the chamber.

Several international and national standards prescribe specific design criteria and explicit sound field requirements for reverberation chambers.[2–7] All accredited labs must adhere to one or more of these standards, depending on which measurement is being performed. Despite the standardized requirements, difficulties with measurement reproducibility and repeatability have been well documented in the literature. In particular, there have been significant quantitative differences in measured absorption coefficient values among laboratories when testing the same specimen.[8–17]

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The standards recommend the use of either rotating or stationary hanging diffuser panels to increase sound field diffusivity. However, both of these diffuser types can have an effect on the ability to characterize the diffusivity of the chamber's sound field, as discussed below. Previous researchers have proposed boundary diffusers, which are attached directly to the interior surfaces of the chamber, as an alternative to both hanging and rotating diffusers.[15,18–21] Although some previous case studies have shown that boundary diffusers can be used to produce an adequately diffuse sound field, no data has been provided that indicates boundary diffusers are preferable. Also, no systematic investigations have been conducted to determine possible optimal boundary diffuser configurations and installations. The current study is the first to detail a systematic comparison of the effectiveness of boundary and hanging diffusers in producing a diffuse sound field as characterized by standardized quantifiers.

II. PREVIOUS RESEARCH

A. Reverberation chambers and sound field diffusivity

Reverberation chamber design first appeared in the literature in the early 1950s.[22–24] Most practical knowledge regarding optimal chamber design has stemmed from case studies of existing chambers,[18,19,25–29] eventually resulting in the codification of the currently preferred chamber design practices through the development of national and international standards.[2–7] These standards detail various procedures for the qualification of reverberation chambers, including quantitative methods for determining whether a chamber possesses an adequately diffuse or reverberant sound field. Of particular interest for the current study are the standards ISO 354, ASTM E90, and ASTM C423, which detail measurements that do not require a reference sound source.[3,6,7] The qualification procedures in these three standards rely on decay rate and sound pressure levels, which can be calculated from impulse response measurements. ISO 17497-1 defers to ISO 354 for design criteria and qualification procedures, and is thus covered ipso facto.[4] Both the ISO 354 and ASTM C423 standards recommend installing hanging or rotating diffusers, and describe a procedure for determining the appropriate number of diffusers based on achieving a maximum absorption coefficient value. ASTM C423 also specifies a maximum allowable standard deviation of decay rate between receivers within the chamber. ASTM E90 prescribes a maximum total confidence interval, which is a weighted root-sum-square of the sound pressure and absorption standard deviation in the chamber. These three standards are used in the data analysis of the current study, as discussed below.

ASTM C423 and ISO 354 both focus on the measurement of the sound absorption coefficient. The direct link between sound field diffusivity and sound absorption coefficient measurement reproducibility is well known in the state-of-the-art, and is substantiated by the long history of the emphasis on diffusivity in the standardized measurement procedures discussed here. Nevertheless, achieving adequate reproducibility continues to be an issue in the field.

Although sound field diffusivity can be increased by adding rotating or hanging diffusers, as prescribed by the standards, both diffuser types can have an effect on the measurement results in the chamber. Rotating diffusers have motors that can add to background noise levels, which may limit the signal-to-noise ratio and invalidate measurement results. The rotating diffuser type also causes the chamber to be a time-variant system, which precludes the use of modern measurement techniques that can allow for higher signal-to-noise ratios and more accurate decay rate measurements than those achievable using the classic interrupted noise method.[30]

Both rotating and hanging diffusers introduce uncertainty when calculating the theoretical mean free path (MFP) of sound energy propagation in the room, which in turn can affect the measured absorption coefficient of the test specimen. Although the concept that a MFP value closer to the theoretical should produce more accurate coefficient values is well-documented in the literature,[31] a short theoretical development is given here.

The theoretical value of the MFP is given as

$$\mathrm{MFP} = 4V/S_{\mathrm{room}}, \tag{1}$$

where V is the volume of the room, and S_{room} is the surface area of the room. When rotating and hanging diffusers are utilized, the effective volume and surface area of the chamber are unknown. In fact, the current standards do not specify whether to include both sides, one side, or no sides of the diffusers when calculating the surface area. Nevertheless, the Sabine (or Eyring) equation used to calculate the room's average absorption coefficient from the measured reverberation time includes the MFP:

$$\bar{\alpha} = \mathrm{MFP} \cdot \left(\frac{6\ln(10)}{cT} - m \right), \tag{2}$$

where c is the speed of sound [m/s], T is the reverberation time [s] of the room, and m is the air attenuation coefficient [m^{-1}]. According to ISO 354, Eq. (2) can be used to obtain the absorption coefficient of a test specimen:

$$\alpha = \mathrm{MFP} \cdot \frac{S_{\mathrm{room}}}{S} \cdot \left(\frac{6\ln(10)}{c_2 T_2 - c_1 T_1} - (m_2 - m_1) \right), \tag{3}$$

where the quantities with index 1 and 2 are found for the empty chamber and for the chamber with the test specimen, respectively, and S is the surface area [m^2] of the test specimen. Equation (3) shows that the MFP linearly scales the result of the absorption coefficient. Hence, if the actual MFP of the chamber differs from the theoretical value, as given in Eq. (1), then an uncertainty in the absorption coefficient could arise. Therefore, the ambiguity of the chamber volume and surface area when using rotating or hanging diffusers can increase uncertainty when calculating the absorption coefficient, which in turn would increase uncertainty when quantifying the chamber diffusivity.

1. Boundary diffusers

Boundary diffusers are defined in the current study as solid forms attached directly to the interior surface of the reverberation chamber. This diffuser type has been referred to as a "volume diffuser" by some previous researchers; however, this term is ambiguous since other researchers use "volume diffuser" to describe objects such as sonic crystals, which are not attached to the room's interior surfaces, and achieve diffusion through a different mechanism.[32,33] Therefore, "boundary diffuser" will be used exclusively in the current paper, and the authors would encourage others to adopt this term for this diffuser type to avoid ambiguity and confusion.

Boundary diffusers have been used as a means of increasing diffusivity in reverberation chambers for over 50 years.[18] Vercammen[15] and Nash[34] have independently suggested boundary diffusers as an alternative diffuser type to be considered for inclusion in future measurement standards. Furthermore, the working group for ISO 354 is considering the inclusion of boundary diffusers in the next revision of the standard. It is posited, by these previous authors and the ISO working group, that the boundary diffuser type would increase the accuracy of the standardized measurement procedures. Uncertainty in the absorption coefficient calculation when using rotating or hanging diffusers was inferred by Vercammen, but the development was not carried to completion. However, the theoretical development of the relationship between MFP and the absorption coefficient provided above could be used as a basis for the hypothesis that boundary diffusers would decrease the uncertainty. The volume and surface area of the chamber is unambiguous when boundary diffusers are implemented. Therefore, the MFP will more closely match the theoretical value when using boundary diffusers than when using rotating or hanging diffusers. As discussed above, a more accurate MFP will result in a more accurate absorption coefficient, and thus will produce a more accurate characterization of the diffusivity of the chamber.

Lautenbach and Vercammen studied a scale model reverberation chamber with a specific configuration of boundary diffusers as compared to a specific configuration of hanging diffusers in the same chamber.[20] They used the standard deviation of reverberation time across receiver position as a quantifier of sound field diffusivity. Their results showed that the standard deviation for the boundary diffusers was lower than for the hanging diffusers, suggesting that the boundary diffusers produced a more diffuse sound field. However, a later presentation by Lautenbach and Vercammen showed results from a full-scale chamber that indicated no significant difference in sound field diffusivity between the two diffuser types.[21] Although these previous researchers have suggested boundary diffusers as an alternative, preferable diffuser type, the limited data available thus far does not support this claim.

These previous studies were only for a specific configuration of hanging and boundary diffusers. So a systematic study of the comparative effect of hanging and boundary diffusers has not been carried out. Additionally, no previous study has characterized the relative effectiveness of the two diffuser types in the context of the standardized quantifiers of sound field diffusivity. The current study presents a systematic comparison of hanging diffusers and three types of boundary diffusers within the context of the currently standardized quantifiers of chamber sound field diffusivity.

III. PURPOSE AND METHODOLOGY

The primary purpose of the current study is to compare and contrast boundary diffusers and hanging diffusers through the reverberation chamber qualification procedures described in ISO 354, ASTM C423, and ASTM E90.

These three standards provide three quantifiers of sound field diffusivity:

(1) maximum absorption coefficient (α_{max});
(2) relative standard deviation of sound decay (s_{rel});
(3) total confidence interval of sound decay and absorption area (CI_{tot}).

A secondary goal of the current study is to analyze the standardized sound field requirements and chamber design specifications to determine the effectiveness of the standardized quantifiers of sound field diffusivity.

A. Scale reverberation chamber

In the current study, a 1:5 scale reverberation chamber has been used. The chamber is constructed of six 2.8 cm thick wooden panels that are finished with a two-component coating lacquer, ensuring high acoustic reflectivity. The interior dimensions of the chamber are 1.2 m $\times$ 1.5 m $\times$ 0.95 m. To ease comparison to other chambers, all diffuser dimensions provided below are given in real-world equivalent form. Additionally, all frequency values referenced in this paper have also already been scaled to real-world equivalent form.

B. Diffusers

Four types of diffusers have been analyzed: hanging, small boundary, large boundary, and mixed boundary. Each type is described in detail below. Table I shows the surface area of a single diffuser of each type. For ease in comparison to other chambers of differing sizes, the aggregate surface area of the diffusers will be represented here as a relative surface area. The relative surface area is calculated as the ratio of total surface area of the diffusers to the total internal surface area of the reverberation chamber. The standards make use of the relative surface area, providing an anecdotal rule of thumb that 0.15 to 0.25 relative surface area is required to achieve satisfactory diffusion in rectangular chambers. Table I also shows the relative surface area value for each diffuser type for the maximum number of diffusers,

TABLE I. Surface area of a single diffuser and maximum relative surface area for each diffuser type.

Diffuser type	Single diffuser surface area (m^2)	Maximum relative surface area
Hanging	2.58	0.21
Small boundary	1.38	0.32
Large boundary	2.75	0.28
Mixed boundary	1.38 and 2.75	0.30

referred to as the maximum relative surface area. This maximum relative surface area was limited by the available installation space in the chamber. (All dimensions given in full-scale equivalent form.)

1. *Hanging diffusers*

According to the ISO 354 and ASTM C423 standards, hanging diffusers should: have a mass per unit area of 5.0 kg/m^3 or greater; have a surface area between 0.8 and 3.0 m^2 (one side); have a corrugated or curved structure; have minimal sound absorption; be positioned and oriented randomly throughout the chamber.[3,6] The hanging diffusers used in this study are constructed of rectangular pieces of 1/4-in. curved plastic, and meet the criteria given in the standards. A maximum of nine randomly oriented hanging diffusers has been used, each with a surface area of 2.58 m^2 (one side).

2. *Boundary diffusers*

All boundary diffusers in the current study are solid hemispherical caps made of layers of hardwood and coated with sound reflective varnish. The height of the caps is 0.35 m and the radius of curvature is 1.25 and 0.625 m for the large and small boundary diffusers, respectively. In calculating the surface area of the chamber for configurations with boundary diffusers, the area of each diffuser that occluded part of the wall area was taken into account when calculating the surface area of the chamber. The decrease in volume due to the spherical caps was also considered when calculating the volume of the chamber for these configurations.

Figure 1 shows the chamber with a hanging diffuser configuration and a mixed boundary configuration. The absorptive test specimen, an 18.5 cm (real-world equivalent thickness) sample of homogenous polyurethane foam, is placed on the floor of the chamber.

C. Measurements

The measurement process began by recording impulse responses of the empty reverberation chamber with and without an absorptive test specimen. For each subsequent measurement, diffusers were added to the chamber in intervals of approximately 3.0 m^2, and the impulse responses of the chamber with and without the specimen were recorded. This process was repeated for each diffuser type until the maximum relative surface area was achieved. Figure 2 depicts this systematic addition of diffusers for 18 configurations of the mixed boundary diffuser type.

All impulse responses have been measured for eight receiver positions and two source positions. The data are similar for both sources, so only one is considered here. The receivers were placed at a height of 1.25 m above the chamber floor; the source was mounted approximately 0.75 m above the floor. A weighted sine-sweep signal was used to excite the reverberation chamber, and the corresponding decay curves have been calculated using the indirect integrated impulse response method.[31] The sweep signal was shaped to have an equal signal-to-noise ratio across all frequencies of interest.

1. *Maximum absorption coefficient and number of diffusers*

Both ISO 354 (Ref. 3) and ASTM C423 (Ref. 7) state that the average absorption coefficient of an absorptive test specimen will increase with an increasing number of diffusers until reaching a maximum value, after which further addition of diffusers will cause the absorption to either remain constant or decrease. The diffuser configuration that produces the maximum absorption is recommended and considered to create an approximately diffuse sound field.

Diffusers serve to improve sound field diffusivity mainly by redirecting incident sound energy, thereby increasing sound field isotropy.[35] Sound propagating horizontally in an empty chamber will tend to remain in the horizontal plane, and very little sound energy will reach the absorptive test specimen that lies on the floor (i.e., in the vertical plane). In a chamber with many diffusers, however, more sound energy is scattered and redirected away from the horizontal plane and into the vertical plane. As more energy is directed toward the specimen, the amount of energy absorbed by the specimen increases, resulting in higher absorption coefficient measurements. This increase in absorption indicates a direct relationship between sound field diffusivity and sound absorption coefficient, a notion confirmed by Toyoda through a computational ray-tracing technique.[1]

Though hanging diffusers, not boundary diffusers, are specifically mentioned in ISO 354 and ASTM C423, theoretical considerations do not limit the placement of diffusers. Therefore, the standardized process described above for determining the appropriate number of diffusers can be generalized to include boundary diffusers.

The standards detail the calculation of the equivalent absorption area of the chamber [m^2] using

$$A = \frac{55.3\,V}{c\bar{T}_{60}} - 4Vm_{\mathrm{iso}}, \tag{4}$$

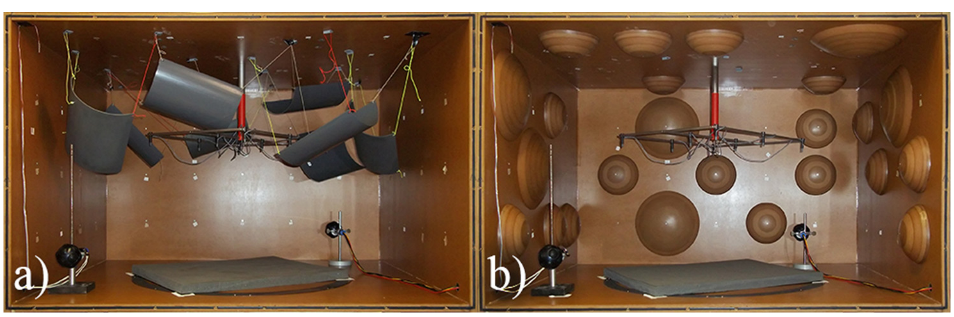

FIG. 1. (Color online) Scale reverberation chamber with (a) hanging diffusers and (b) mixed boundary diffusers.

FIG. 2. (Color online) Eighteen configurations of the reverberation chamber showing the systematic increase in number of mixed boundary diffusers.

which is developed from Eq. (2), where A is defined as the hypothetical area of a perfectly absorbing surface (without diffraction effects), which, if it were the only absorbing element in the chamber, would give the same reverberation time as the chamber under consideration.[3] V is the volume of the chamber [m^3], c is the speed of sound [m/s], and T_{60} is the reverberation time [s] averaged over receiver position. The current study uses the T_{30} (-5 to -35 dB) metric rather than the T_{60} (-5 to -60 dB), assuming no loss in accuracy. Finally, m_{iso} is the air attenuation coefficient [m^{-1}], calculated according to ISO 9613$-$1 (Ref. 36).

The sound absorption coefficient of the absorptive specimen can then be found using

$$\alpha = \frac{A_2 - A_1}{S}, \tag{5}$$

where A_1 is the equivalent absorption area of the empty reverberation chamber and A_2 is the equivalent absorption area of the chamber with the absorptive test specimen installed [both are calculated using Eq. (4)], and S is the surface area [m^2] of the test specimen, as defined for Eq. (3). The mean value of the sound absorption coefficient, averaged over receiver position and frequency (500–5000 Hz), has been calculated for each diffuser configuration. The resulting absorption data for all configurations are presented and examined below in Sec. IV.

It is important to note that the absorption coefficient calculation is dependent on the volume of the chamber, as indicated in Eq. (4). Since adding boundary diffusers decreases the volume of the chamber, the V value in Eq. (4) must be appropriately updated as the diffuser configuration changes in order to accurately calculate the absorption coefficient.

2. Decay rate relative standard deviation

ASTM C423 also prescribes maximum values for the variation of decay rate across receiver position with no specimen installed. Based on this standard, decay rates are calculated from the measured reverberation times using the formula

$$d_i = \frac{60}{T_i} - m_{\mathrm{iso}}\, c \log_{10}(e), \tag{6}$$

where d_i is the decay rate measured at the ith receiver position, T_i is the reverberation time at the ith position, and the other variables defined as above.

The standard deviation of decay rate across receiver position is then calculated at each 1/3 frequency octave band between 100 and 5000 Hz, using

$$s = \left(\frac{1}{N-1} \sum_{i=1}^{N} (d_i - \bar{d})^2 \right)^{1/2}, \quad (7)$$

where s is the standard deviation of decay rate, N is the number of receiver positions, and $\bar{d}$ is the decay rate averaged over all receiver positions. Finally, the relative standard deviation of decay rate, s_{rel}, is calculated using $s_{rel} = s/\bar{d}$. The relative standard deviation of decay rate has been calculated for each diffuser configuration; the resulting data are presented in Sec. IV below.

3. *Total confidence interval*

ASTM E90 describes the calculation of the total confidence interval (CI_{tot}) quantifier for coupled reverberation chambers.[7] This standard focuses on sound transmission loss tests through partitions, which requires two connected reverberation chambers. Since the current study uses only one chamber, any values corresponding to the "second chamber" have been set equal to zero so that the CI_{tot} values calculated here are describing the behavior of the single chamber.

First, the standard deviation of sound pressure level across receiver position is calculated according to the formula

$$s_L = \left(\frac{1}{N-1} \sum_{i=1}^{N} (L_i - \bar{L})^2 \right)^{1/2}, \quad (8)$$

where N is the number of receiver positions, L_i is the sound pressure level [dB] measured at the ith receiver position, and $\bar{L}$ is the sound pressure level averaged over all receiver positions. Next, the standard deviation of equivalent absorption area across receiver position is calculated using

$$s_A = \left(\frac{1}{N-1} \sum_{i=1}^{N} (A_i - \bar{A})^2 \right)^{1/2}, \quad (9)$$

where A_i is the equivalent sound absorption area [m^2] measured at the ith receiver position calculated as per ASTM C 423, and Eq. (4) above, and $\bar{A}$ is the equivalent sound absorption area averaged over all receiver positions. Next, the 95% confidence intervals are calculated for both sound pressure level and equivalent absorption area, using $\Delta X = as$, where ΔX is the 95% confidence interval, s is the standard deviation of either absorption or sound pressure level, and a is a factor that depends on the number of measurements, N. The values for a are given in ASTM E90 table A2.1. Finally, the two confidence intervals are combined to give the total confidence interval:

$$CI_{tot} = \sqrt{(\Delta L)^2 + 18.9 \left(\frac{\Delta A}{\bar{A}} \right)^2}, \quad (10)$$

where ΔL and ΔA are the confidence intervals for sound pressure level and equivalent absorption area, respectively. The total confidence interval has been calculated for each diffuser configuration; the resulting data are presented and analyzed in Sec. IV below.

IV. RESULTS AND ANALYSIS

The three quantifiers discussed above, maximum absorption coefficient (α_{max}), standard deviation of decay rate (s_{rel}), and total confidence interval (CI_{tot}), have been calculated according to ISO 354, ASTM C423, and ASTM E90.

A. Maximum absorption coefficient and number of diffusers

The appropriate number of diffusers is determined by finding the maximum absorption coefficient of a test specimen (α_{max}), calculated as per ASTM C423 or ISO 354, as a function of diffuser surface area. A maximum coefficient value followed by constant or decreasing values as more diffusers are added is meant to suggest a high degree of sound field isotropy for the diffuser configuration that produces the maximum value.

Figure 3 shows the absorption coefficient of the test specimen for each diffuser type as a function of relative surface area. For all diffuser types, the absorption coefficient increases appreciably as additional diffusers are added to the chamber, which is the anticipated behavior described in the standards. However, the boundary diffuser types do not produce a maximum value followed by constant or decreasing values. Rather, the data trends indicate a continued increase in the coefficient values. According to the standards, this result suggests additional boundary diffusers are required to achieve an adequately diffuse sound field. For each boundary diffuser type, the maximum number of diffusers were installed, so no additional diffusers could be added.

In contrast to the boundary diffusers, the hanging diffusers produce a definite maximum absorption coefficient: $\alpha_{max} = 0.95$ at approximately 14% relative surface area. This result suggests that hanging diffusers produce an adequately diffuse sound field, since the maximum value was reached, as specified in the standards.

However, this α_{max} is lower than those produced by the boundary diffusers. This lower coefficient value suggests

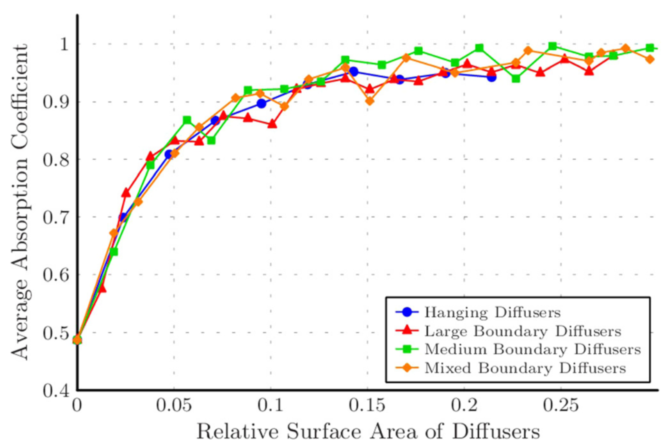

FIG. 3. (Color online) Average absorption coefficients as a function of relative diffuser surface area for four types of diffusers.

that the hanging diffusers do not sufficiently redirect the horizontal sound field into the vertical sound field, which would prevent energy from reaching the absorptive test specimen. As discussed in Sec. III C 1, the lower absorption coefficient for the hanging diffusers may indicate that the field is not sufficiently diffuse.

So this particular diffusivity quantifier (α_{max}) simultaneously indicates that the hanging diffusers result in an adequately diffuse sound field and that the field is not sufficiently diffuse. These are clearly contradictory conclusions. Therefore, based on this quantifier, it is unclear whether any of the diffuser types are actually more effective, or if any are completely effective at all. It should also be noted that each diffuser type produces somewhat different absorption coefficients. However, since a "true" absorption coefficient cannot be definitively determined, these results do not allow for the identification of an ideal diffuser type.

Previous researchers have suggested using a "known" absorptive test specimen to calibrate the reverberation chamber.[37] A similar technique could be used to better understand which diffuser type is more effective. However, a calibration specimen has not been developed for scale testing. Therefore, this technique was not employed in the current study. Future work may explore this option.

B. Relative standard deviation of decay rate

ASTM C423 details the calculation of the relative standard deviation of decay rate across receiver position (s_{rel}). Lower values of s_{rel} indicate higher values of sound field homogeneity and, hence, higher sound field diffusivity.

Figure 4 shows s_{rel} as a function of frequency for each diffuser type. The black line in the figure shows the maximum allowable s_{rel} values from ASTM C423. All diffuser types exhibit similar data trends, except for the spike at 200 Hz for the large boundary diffusers. This result suggests that the boundary diffusers are not preferable to the hanging diffusers according to this diffusivity quantifier. However, none of the diffuser types satisfy the maxima s_{rel} criteria across all frequency bands and, though there is fluctuation, no diffuser type produces definitively lower s_{rel} values.

It should be noted that ASTM C423 does not specify which diffuser configuration should be analyzed when calculating s_{rel}. For initial analysis in the current study, the data shown in Fig. 4 correspond to the configuration that produced the highest absorption coefficient value for each diffuser type (according to the data shown in Fig. 3).

For further analysis, the configuration that had the lowest relative standard deviation across all frequencies was identified for each diffuser type. Figure 5 shows the s_{rel} data for these configurations with the corresponding diffuser relative surface area shown in the figure legend. None of these configurations meet the standard maxima criteria, although they do more closely conform to the standard than the maximum absorption coefficient configurations.

The major difference between the s_{rel} data shown in Figs. 4 and 5 is that the diffuser relative surface areas are much lower for the configurations that produced the lowest relative standard deviations. This difference suggests a high disparity between the conclusions based on the two diffusivity quantifiers discussed so far. For example, looking at the hanging diffusers, the α_{max} data indicate that 14% relative surface area is the ideal number of diffusers. The s_{rel} data suggest that 7% relative surface area is preferred. This result corresponds to *half* the number of diffusers.

The two quantifiers not only suggest different ideal relative surface areas of diffusers, they also give differing absorption coefficient results for the same test specimen.

Figure 6 shows the absorption coefficient data for (1) the ideal hanging diffuser configuration according to α_{max}, (2) the hanging diffuser configuration that produced the lowest s_{rel}, and (3) the configuration with no diffusers (as a base comparison). The s_{rel} configuration produces absorption data that is approximately 10% lower than the α_{max} configuration in the mid- and high-frequencies. A 10% difference is an appreciable amount for this acoustic quantity. Figure 6 shows data for only the hanging diffusers; all other diffuser types produced very similar graphs.

Both the α_{max} and s_{rel} quantifiers appear in standard ASTM C423, yet they produce very different results. If both quantifiers truly measured sound field diffusivity, it is expected that they would agree on an ideal diffuser

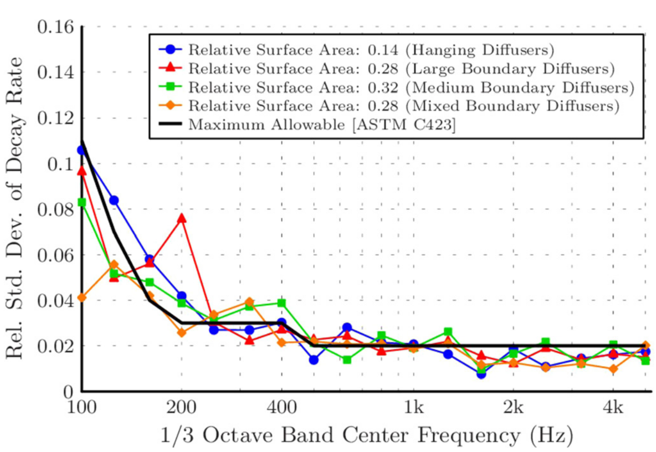

FIG. 4. (Color online) Relative standard deviation of decay rate versus frequency for each diffuser type (configurations that produced the highest absorption coefficient value).

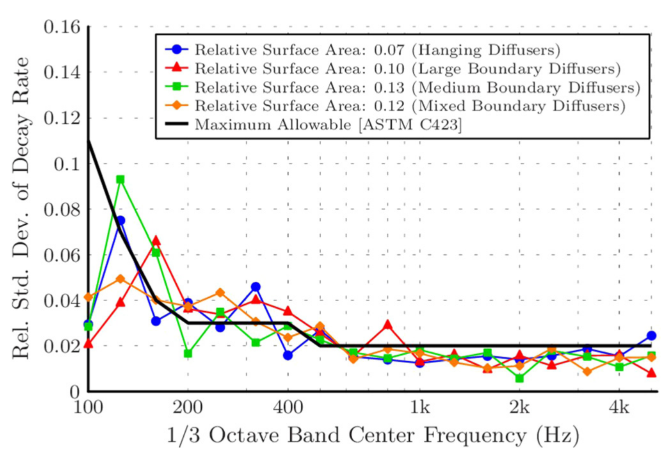

FIG. 5. (Color online) Relative standard deviation of decay rate versus frequency for each diffuser type (configurations that produced the lowest relative standard deviation across all frequencies).

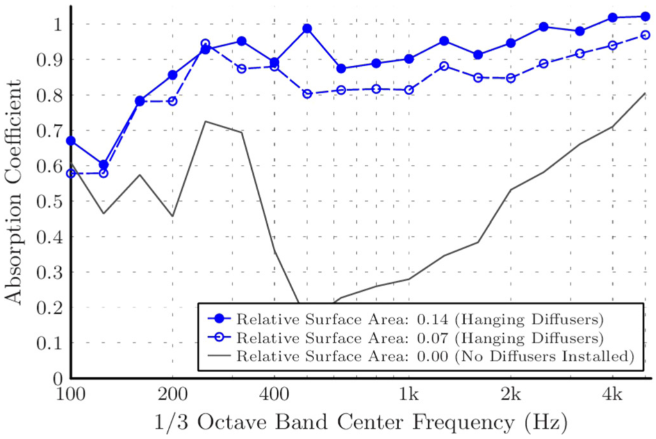

FIG. 6. (Color online) Absorption coefficient as a function of frequency for (1) the hanging diffuser configuration recommended by the maximum absorption coefficient quantifier, (2) the hanging diffuser configuration that produced the lowest relative standard deviations of decay rate, and (3) the configuration with no diffusers.

configuration and on the absorption data for a specific specimen. They do not agree, however, suggesting that one or both of the quantifiers does not adequately or accurately quantify sound field diffusivity, and that the standard contains certain inherent inconsistencies.

C. Total confidence interval

The total confidence interval (CI_{tot}) is calculated as per ASTM E90, as described above, using both the standard deviation of absorption and the standard deviation of sound pressure level. The CI_{tot} quantifies sound field diffusivity and the repeatability of measurements; lower CI_{tot} values signify high degrees of diffusivity, accuracy, and precision.

ASTM E90 also does not specify which configuration to analyze, so the configurations producing the maximum absorption coefficient (according to the data shown in Fig. 3) have been chosen for initial analysis.

Figure 7 shows the CI_{tot} data for these configurations as a function of frequency for each diffuser type. The black line in Fig. 7 shows the maximum CI_{tot} values allowed by ASTM E90. All diffuser types produce very similar trends and satisfy the criteria from the standard at every frequency band,

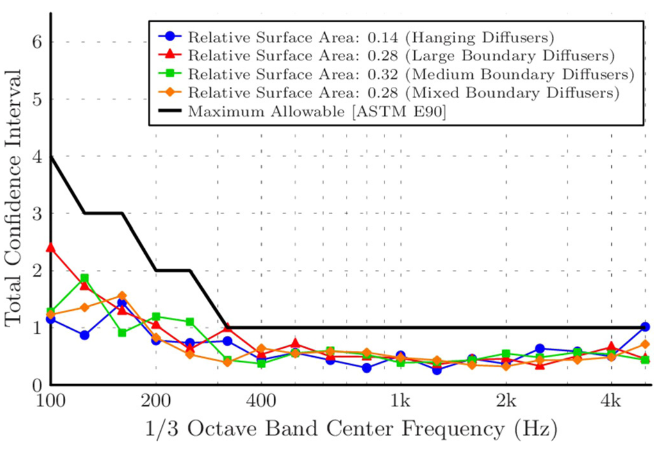

FIG. 7. (Color online) Total confidence interval versus frequency for each diffuser type, as well as maximum from ASTM E90.

except the hanging diffusers at 5000 Hz (which exceeds the maximum by a negligible amount). This result suggests that the boundary diffusers are not preferable to the hanging diffusers according to this diffusivity quantifier. All configurations easily meet the CI_{tot} requirements but fail to meet the s_{rel} requirements, which may suggest that the CI_{tot} is not a sufficiently stringent quantifier.

The CI_{tot} data for no other configurations will be shown here because, with few exceptions for specific 1/3 octave bands, all configurations produce CI_{tot} values that fall below the maxima from the standard. *This is true even for the configuration with no diffusers*. This result supports the claim that the CI_{tot} is not a sufficiently stringent quantifier.

To better understand why this may be the case, the two components of the CI_{tot}, sound pressure level and absorption standard deviations, as detailed in Eq. (10), have been analyzed independently and compared. For all configurations, the sound pressure level component contributes approximately 90%–95% to the CI_{tot}, while the absorption component only contributes 5%–10%, with few exceptions. Therefore, the sound pressure level component is the dominant factor that determines whether or not the standardized maxima criteria are being met. This result suggests that the CI_{tot} quantifier may need to be broken into two separate components to more precisely quantify diffusivity in a reverberation chamber.

V. CONCLUSIONS AND OUTLOOK

A 1:5 scale reverberation chamber has been used to determine the relative efficacy of hanging, large boundary, small boundary, and mixed boundary diffusers. To that end, three acoustical quantifiers have been measured: maximum absorption coefficient (α_{max}), the relative standard deviation of decay rate (s_{rel}), and the total confidence interval (CI_{tot}).[7] The data trends for all diffuser types are all very similar for all diffusivity quantifiers, implying that boundary diffusers and hanging diffusers achieve roughly equivalent diffusion. The motivating hypothesis for this was that boundary diffusers would allow for a more accurate calculation of the chamber volume and surface area, which in turn would increase the accuracy of the absorption coefficient and the characterization of the sound field diffusivity in the chamber. The fact that the data for all diffuser types are relatively similar does not support this hypothesis; however, these data indicate, at the very least, that boundary diffusers are adequate alternatives to hanging diffusers.

On the other hand, there are contradictions in the conclusions drawn from each of the standardized quantifiers. The α_{max} quantifier data are inconclusive and do not clearly indicate whether diffusivity is achieved by any of the diffuser types. The s_{rel} quantifier suggests insufficient sound field diffusivity for all diffuser types, especially in the lower frequencies. The CI_{tot} quantifier indicates that all diffuser types produce adequate sound field diffusivity for all frequency bands. Also, the α_{max} and s_{rel} quantifiers suggest different optimal numbers of diffusers and different test specimen absorption coefficients.

The discrepancy between the three acoustic sound field diffusivity quantifiers reveals possible ambiguities, inconsistencies, and contradictions in the standards. These problems suggest that the standards prescribe inconsistent reverberation chamber qualification procedures, which could be the cause of low inter-laboratory reproducibility. Since the standardized quantifiers seemingly do not accurately rate diffusivity, this may suggest that the true comparison between hanging and boundary diffusers cannot be determined using these standardized quantifiers. It is possible that there exists an appreciable difference in the efficacy of the hanging and boundary diffusers: a difference that could be determined using more accurate quantifiers.

The current study has produced a rich set of data, and the authors plan to further evaluate the data while exploring alternative quantifiers which may more accurately and precisely describe sound field diffusivity in a reverberation chamber. Future work could include an investigation of the effect of diffuser type on sound field isotropy using multi-directional receivers (e.g., spherical microphone). Additionally, an analysis could be carried out to study boundary and hanging diffusers installed simultaneously in the chamber. Furthermore, an investigation of the role of boundary diffuser shape is also possible (as only hemispherical diffusers have been used in this study). Resonating boundary diffusers, previously introduced by one of the current authors,[38] could also be included in future work.

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