The effective air absorption coefficient for predicting reverberation time in full octave bands

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A substantial amount of research has been devoted to producing a calculation model for air absorption for pure tones. However, most statistical and geometrical room acoustic prediction models calculate the reverberation time in full octave bands in accordance with ISO 3382-1 (International Organization for Standardization, 2009). So far, the available methods that allow calculation of air absorption in octave bands have not been investigated for room acoustic applications. In this paper, the effect of air absorption on octave band reverberation time calculations is investigated based on calculations. It is found that the approximation method, as described in the standard ANSI S1.26 (American National Standards Institute, 1995), fails to estimate accurate decay curves for full octave bands. In this paper, a method is used to calculate the energy decay curve in rooms based on a summation of pure tones within the band. From this decay curve, which is found to be slightly concave upwards, T_{20} and T_{30} can be determined. For different conditions, an effective intensity attenuation coefficient $m_{B;\mathrm{eff}}$ for the full octave bands has been calculated. This $m_{B;\mathrm{eff}}$ can be used for reverberation time calculations, if results are to be compared with T_{20} or T_{30} measurements. Also, guidelines are given for the air absorption correction of decay curves, measured in a scale model. © *2014 Acoustical Society of America*. [http://dx.doi.org/10.1121/1.4901710]

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I. INTRODUCTION

A. Air absorption

In 1929, it was Sabine[1] who first noticed a variation in the reverberation time of an empty reverberation room in his laboratory, caused by different ambient conditions. In 1931, Knudsen[2] proved that this effect was not caused by a change of acoustical absorption properties of the surface material, but by the change of acoustical absorption properties of the air, when temperature and humidity change. A substantial amount of research has been devoted to producing a calculation model for pure tone air absorption based on sound decay measurements in reverberation rooms[1–4] and impedance tubes or spheres,[5–10] with varying frequency ranges, gas mixtures, and ambient conditions. The final calculation model is explained in literature[11–13] and has been incorporated in currently used national and international standards for the calculation of the absorption of sound by the atmosphere ANSI S1.26 (Ref. 14) and ISO 9613–1.[15] While the model calculates air absorption in pure tones, most statistical and geometrical room acoustic prediction models calculate the reverberation time and other room acoustic parameters in full octave bands. So far, the available methods that allow calculation of air absorption in octave bands have not been investigated for room acoustic applications. In this paper, the effect of air absorption on octave band reverberation time estimations is investigated based on calculations.

Over time, the research point of view of air absorption has varied from the propagation of sound outdoors, to room acoustics, and to high frequency sound propagation applications. As a result, different names have been used for the same phenomenon, where the medium is referred to as air or atmosphere and the process as absorption or attenuation. The various research viewpoints also led to the use of three types of coefficients based on sound pressure level, sound intensity, and sound pressure. The three types of coefficients with different units can be converted by Eq. (1), as was described in a footnote of a textbook by Knudsen and Harris,[16]

$$A = 10\log_{10}(e)\cdot m = 20\log_{10}(e)\cdot \alpha, \tag{1}$$

where A is the atmospheric attenuation coefficient in dB/unit length, m is the intensity attenuation coefficient in (unit length)$^{-1}$, and α is the pressure attenuation coefficient in Np/unit length.

Confusingly, the ANSI S1.26 and ISO 9613-1 standards use the coefficient α to denote the atmospheric attenuation coefficient in dB/m or dB/km in contrast to the coefficient A in Eq. (1). Because this paper deals with room acoustics, the phenomenon will be referred to as "air absorption" and the intensity attenuation coefficient m is used.

B. Air absorption in room acoustic prediction modeling

Most statistical calculation models that predict the reverberation time, for instance, Sabine's and Eyring's equation, take into account the air absorption by the factor m:

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$$T_{\text{Sabine}} = 55.3 \cdot \frac{V}{c[A_{\text{mat}} + 4\,\text{mV}]}, \qquad (2)$$

$$T_{\text{Eyring}} = 55.3 \cdot \frac{V}{c[-S \cdot \ln(1-\alpha_{\text{avg}}) + 4\,\text{mV}]}, \qquad (3)$$

where V is room volume, c is speed of sound, A_{mat} is total material absorption, S is material surface, and α_{avg} is average material absorption coefficient.

In geometrical room acoustic prediction models, e.g., the image-sources method or ray-tracing, the air absorption can be estimated by multiplying the distance that the sound "ray" or "particle" travels by the air absorption for this distance. A third modeling method is the use of a physical scale model, where either the air in the model needs to be treated to achieve correct air absorption properties, or the measured impulse responses are corrected mathematically for the error in air absorption. For the prediction of acoustic parameters like reverberation time, it is common to judge octave bands up to 4 kHz, sometimes 8 kHz. For auralization purposes, it is necessary to predict T up to the 16 kHz octave band. In scale model measurements, one might even measure up to the 64 kHz octave band when using a sound device with a 192 kHz sample rate. This paper mainly focuses on the frequency range 2 to 16 kHz for predictions of reverberation time, except for the section on scale modeling.

The reverberation time and other room acoustic parameters are often presented per frequency band. When judging performance spaces and other rooms, full octave bands are commonly used, as described in ISO 3382-1.[17] For measuring material properties, like sound absorption in accordance with ISO 354 (Ref. 18) and sound scattering following ISO 17497,[19] 1/3-octave bands are commonly used. In applications of the above-mentioned methods using frequency bands, it is common to estimate the effect of air absorption by using the center frequency of the band in the pure tone calculation of air absorption as described in ANSI S1.26 or ISO 9613-1. In this paper, both 1/3 and full octave bands will be investigated; however, the main focus lies on the prediction of reverberation time in full octave bands.

For large propagation distances, air absorption shapes the received spectrum[20] as it is frequency dependent. As a result, the effect of air absorption on the energy decay per unit distance for frequency bands is dependent of the distance the sound has traveled. This must be accounted for when predicting the air absorption in frequency band calculations. The "edge frequency method," as first described in the standard ARP 866A (Ref. 21) by Harris as a rule of thumb, illustrates the possible impact of this effect. According to this edge frequency method, for 1/3-octave bands above 4 kHz, air absorption could be estimated using the lower edge frequency of the band. Above 2 kHz the amount of air absorption rapidly increases with frequency. From a sound absorption point of view, the air absorption in the upper part of a frequency band will contribute the most to the average amount of absorption within that band. On the other hand, the calculated reverberation time will be dominated by the lowest frequency (range) within the band for which air absorption has the smallest effect. When predicting reverberation time by modeling the sound field in octave bands, the effect of air absorption might indeed be overestimated when using the pure tone air absorption calculated for the center frequency of the frequency band and the predicted T will be too low. However, whether the edge frequency method results in an accurate approximation has never been investigated for room acoustic purposes.

C. Methods to predict octave band air absorption

An empirical method to estimate air absorption for frequency bands is described in ANSI S1.26 Annex E,[14] the so-called "approximation method,"

$$\delta L_B(f_k, x) = \delta L(f_m, x) \times \{1 + (B_r^2/10)(1 - 0.2303\,\delta L(f_m, x)\}^{1.6}, \qquad (4)$$

where $\delta L_B(f_k,x)$ is the band level attenuation in dB at distance x for the (fractional) octave band with middle frequency f_k; $\delta L(f_m,x)$ is the pure tone level attenuation in dB for the middle frequency f_m within the band, and B_r is the relative bandwidth $(f_2 - f_1)/f_m$, where f_2 is the upper frequency band limit and f_1 is the lower frequency band limit.

This approximation method can be easily applied for the prediction of air absorption on (outdoor) sound propagation. However, for statistical room acoustical calculations, when predicting the reverberation time (T), the use of the approximation method is not straightforward. The distance x that sound has traveled at T seconds could be expressed by cT, with c equal to adiabatic speed of sound, as proposed in ANSI S1.26, par. 6.3. However, this distance is still unknown because T is unknown, so T could only be calculated by the use of iteration. And, when iteration is applied in this way, it is assumed that the energy decay due to air absorption is constant over time, which, for frequency bands, is not the case (this will be further explained in Sec. II B). To avoid the iteration process, Sisler and Bass[22] proposed to calculate the actual sound decay expressed in "power spectral density," using Eyrings' equation, taking into account the change in amount of air absorption over time by integrating over the frequency band:

$$\int_{f_{-1}}^{f_1} W(f,0)df = 10^6 \int_{f_{-1}}^{f_1} W(f,0)e^{-mx}(1-\alpha_w)^{x/m}df, \qquad (5)$$

where W is the power spectral density, f_{-1} and f_1 are the practical integration limits, and $x = ct$.

From this calculated decay, the -60 dB point was determined to obtain the reverberation time. They concluded that, for a room with little sound absorption (painted concrete surfaces), the maximum variation between calculated reverberation times for a pure tone and those predicted for an ideal 1/3-octave band filter is 1.1% and for a real 1/3-octave band filter is 6.8% within the frequency range of 80 to 10 000 Hz. The frequency at which the maximum error occurs is not mentioned in the paper. For a room with substantial sound absorption and a reverberation time of only 0.1 s, they found no difference between calculated reverberation times for a pure tone and those predicted for any 1/3-

octave band filter at frequencies above 1 kHz, clearly because material absorption dominates at such a very low reverberation time. The authors used a pink noise spectrum, but they note that if the spectrum rolled off more rapidly, the differences would be exaggerated. Also, they noted that a full octave band filter would lead to greater differences than the 1/3-octave bands used in their research.

Effects of filtering on T have also been investigated by Jacobsen and Rindel[23] and Kob and Vorlander.[24] They concluded that filter effects should be taken into account when BT, the product of bandwidth and reverberation time, is less than 4. This only occurs at (very) low frequencies, and because air absorption is only significant for T at high frequencies, these filter effects can be neglected for the purpose of this paper.

D. Overview of the paper

In this paper, the impact of air absorption on reverberation time calculations in both 1/3 and full octave bands using a single "effective" air absorption coefficient per band, instead of a calculation based on the pure tones air absorption values, is investigated for diffuse field conditions. Also, the application of the approximation method in room acoustics is tested. In Sec. II, the method used to compute the reverberation time and effective air absorption coefficient will be presented. The results of the various ways of including air absorption in (1/3) octave band calculations of the reverberation time are shown in Sec. III. The implications and guidelines that follow from the calculated results are discussed in Sec. IV, and this paper ends with conclusions.

II. METHOD

A. Equations for calculation of the decay curves

The starting point is exponential energy decay due to material absorption and room volume. And the reverberation time of this decay, without taking into account air absorption, is a given factor, denoted $T_{\mathrm{w/o\_air\_abs}}$. To investigate the impact of air absorption on reverberation time, the decay of sound in a room can be written as a product of two exponential functions. The first exponential function described the decay due to the material absorption and room volume, and the second exponential function depends on the air absorption and distance:

$$I(t) = I(0)\exp\left(\frac{-6\cdot\ln(10)}{T_{\mathrm{w/o\_air\_abs}}}t\right)\exp(-mx), \tag{6}$$

where $I(t)$ is the intensity at time t, $I(0)$ is intensity in dB at $t=0$, x is distance and $x=ct$.

The first exponential function results in a decay equal to -60 dB for $\mathrm{t}=T_{\mathrm{w/o\_air\_abs}}$, and the second, $\exp(-mx)$, expresses the additional decay by air absorption by the intensity attenuation coefficient, m, and distance x.

To determine the influence of a varying amount of air absorption within a frequency band, a similar method is used following Sisler and Bass[22] in this paper denoted the "summation method." Assuming that the sound absorption by materials is equal within a frequency band and using an average over discrete pure tone frequency steps with a logarithmic spacing, Eq. (6) can be written as

$$L_{I;B;\mathrm{sum}}(t,f_{\mathrm{oct}}) = 10\log_{10}\left[I_0(f_i)\exp\left(\frac{-6\cdot\ln(10)}{T_{\mathrm{w/o\_air\_abs}}}t\right)\right] + 10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}I_0(f_i)\exp(-m(f_i)ct)\right], \tag{7}$$

where $L_{I;B;\mathrm{sum}}$ is the intensity level at t for the (1/3) octave band using summation, $m(f_i)$ is the frequency dependent intensity attenuation coefficient in m^{-1} and n, the number of pure tone frequencies within an octave band using logarithmic spacing (in this paper $n=96$ has been used).

To calculate the decay curve including air absorption using the approximation method, as described in ANSI S1.26 Annex E, the following equation is used:

$$L_{I;B;\mathrm{app}}(t,f_{\mathrm{oct}}) = 10\log_{10}\left[I_0(f_i)\exp\left(\frac{-6\cdot\ln(10)}{T_{\mathrm{w/o\_air\_abs}}}t\right)\right] - \delta L(f_m,t) \times \left\{1+\left(B_r^2/10\right)\left(1-0.2303\delta L(f_m,t)\right)\right\}^{1.6}, \tag{8}$$

where $L_{I;B;\mathrm{app}}$ is the intensity level at t for the (1/3) octave band using the approximation method; see Eq. (4).

From the decay curve, calculated using Eq. (7) or (8), the reverberation time including the effect of air absorption is determined, denoted $T_{\mathrm{with\_air\_abs}}$. And to study the effect of air absorption in frequency bands, an effective frequency band intensity attenuation coefficient $m_{B;\mathrm{eff}}$ is determined from $T_{\mathrm{with\_air\_abs}}$ and $T_{\mathrm{w/o\_air\_abs}}$:

$$m_{B;\mathrm{eff}} = \frac{6\cdot\ln(10)}{c}\left[\frac{1}{T_{\mathrm{with\_air\_abs}}} - \frac{1}{T_{\mathrm{w/o\_air\_abs}}}\right]. \tag{9}$$

Any frequency dependency of acoustical properties within the frequency band, like sound absorption and scattering, are neglected to be able to study the effect of air absorption only. It should be noted that, especially at frequencies below 8 kHz, material absorption usually dominates over air absorption and abrupt changes in material sound absorption within a (1/3) octave band might be more problematic than the changes in air absorption within that band.

B. Deriving reverberation time and effective frequency band intensity attenuation coefficient

Because $m(f_i)$ changes with frequency and lower frequencies persist longer, the band limited decay curve $I(t)$ is no longer purely exponential. Consequently, $L_{I;B}(t)$ is not straight but tends to be slightly concave upwards (see Fig. 1). To determine T from the broadband decay curve, Sisler and Bass[21] determined the time it takes for the total sound level to decay by 60 dB. However, in practice, for measured as well as predicted T, it is common to determine T by a (straight-line)

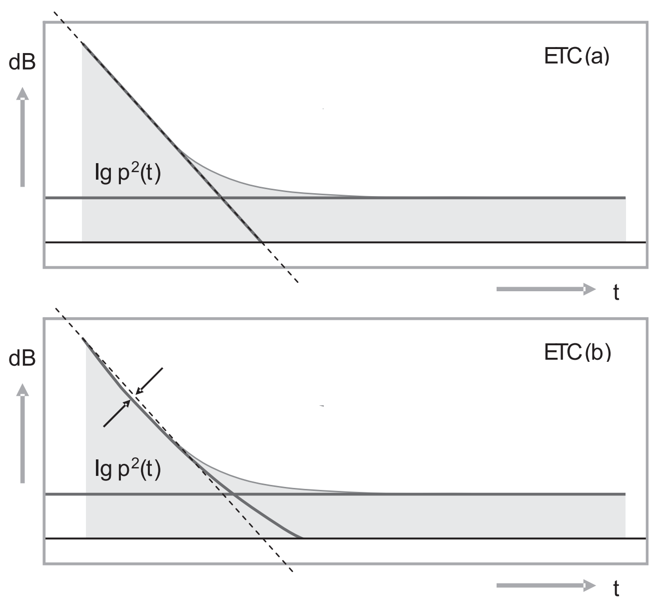

FIG. 1. Because air absorption changes with frequency and low frequencies persist longer, the band limited decay curve is no longer purely exponential. Consequently, the decay curve is not straight but tends to be slightly concave upwards. In the upper figure, showing Energy Time Curve, ETC, (a), a decay curve is shown following a straight line. In the lower figure, showing ETC (b), a decay curve is shown that is slightly concave upwards and no longer parallel to a straight line [to be able to show the effect in this figure, the curvature of ETC (b) is somewhat exaggerated].

least square fit over a 20 or 30 dB decay of the decay curve starting at −5 dB. In the case of using the integrated impulse method, the pressure squared response would first be backwards integrated (Schroeder curve[25]). However, for calculated energy decay curves backwards integration is not necessary when the slope is linear. The resulting reverberation time parameters derived from the curve fit are denoted T_{20} and T_{30}, respectively. In accordance with ISO 3382-1, a decay range of 35 to 45 dB is needed to accurately determine T_{20} and T_{30}, respectively (the decay range can be estimated using the room Impulse to Noise Ratio).[17,26] In Sec. III, T_{20} will be used as the reverberation time definition. As a starting point, a pink noise spectrum is used for the intensity $I(0)$, in accordance with ISO 3382-1, which recommends pink noise for reverberation time measurements using the interrupted noise method. It should be noted that ISO 3382-1 alternatively suggests using Maximum Length Sequence or swept sine signals which in general have a white noise spectrum. Therefore, it is also investigated how other types of source spectra would influence the impact of air absorption (which is only possible using the summation method).

III. CALCULATION RESULTS

A. Approximation method versus summation method

The approximation method, see Eq. (4), assumes a fixed increase of the air attenuation coefficient per frequency within the frequency band. This way, band attenuation can be estimated by a ratio between the amount of air absorption in dB for the band $\delta L_B(f_k,x)$ and pure tone $\delta L(f_m,x)$ as a function of $\delta L(f_m,x)$. Figures 2(a) and 2(b) show this ratio for the 1/3-octave band ($B_r^2/10 = 0.005$) and full octave band ($B_r^2/10 = 0.05$) using ideal filters. The ratio can also be calculated using the summation method for the impact of air absorption (note that the material absorption is not relevant here). In Fig. 2(a), the ratio between $\delta L_B(f_k)$ and $\delta L(f_m)$ is presented for the four octave bands 2 to 16 kHz using the summation method, for Temp = 20 °C, relative humidity (RH) = 50%, and pink noise spectrum (in this paper, the temperature is denoted "Temp" instead of the standardized "T" to avoid confusion with the term reverberation time T). There is a significant difference between the ratio for the different methods and bandwidths. The results for the summation method in Fig. 2(a) show that, for the 2 kHz band, the ratio is higher than the ratio for the three other bands calculated. The ratio, calculated using the approximation method for the octave band, continues to

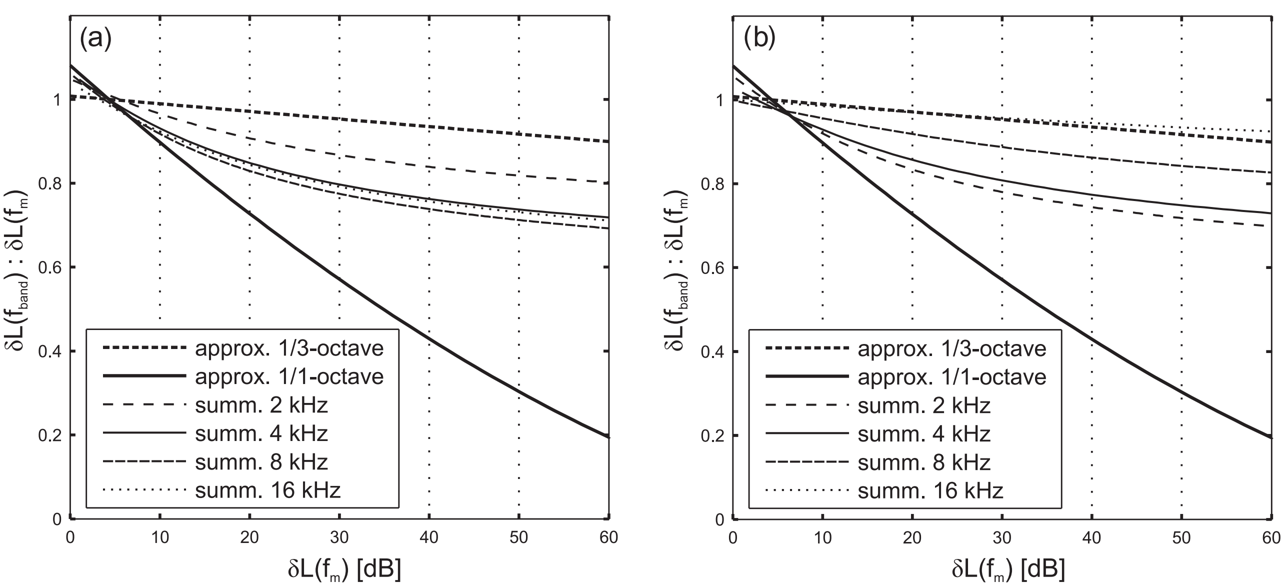

FIG. 2. The ratio between $\delta L_B(f_k)$ and $\delta L(f_m)$ as a function of $\delta L(f_m)$ using the approximation method, Eq. (4), for any 1/3 and full octave band, and using the summation method, Eq. (7), for the full octave bands 2 to 16 kHz. Subplot (a): Results for Temp = 20 °C and RH = 50%. In subplot (b): Results for Temp = 10 °C and RH = 30%.

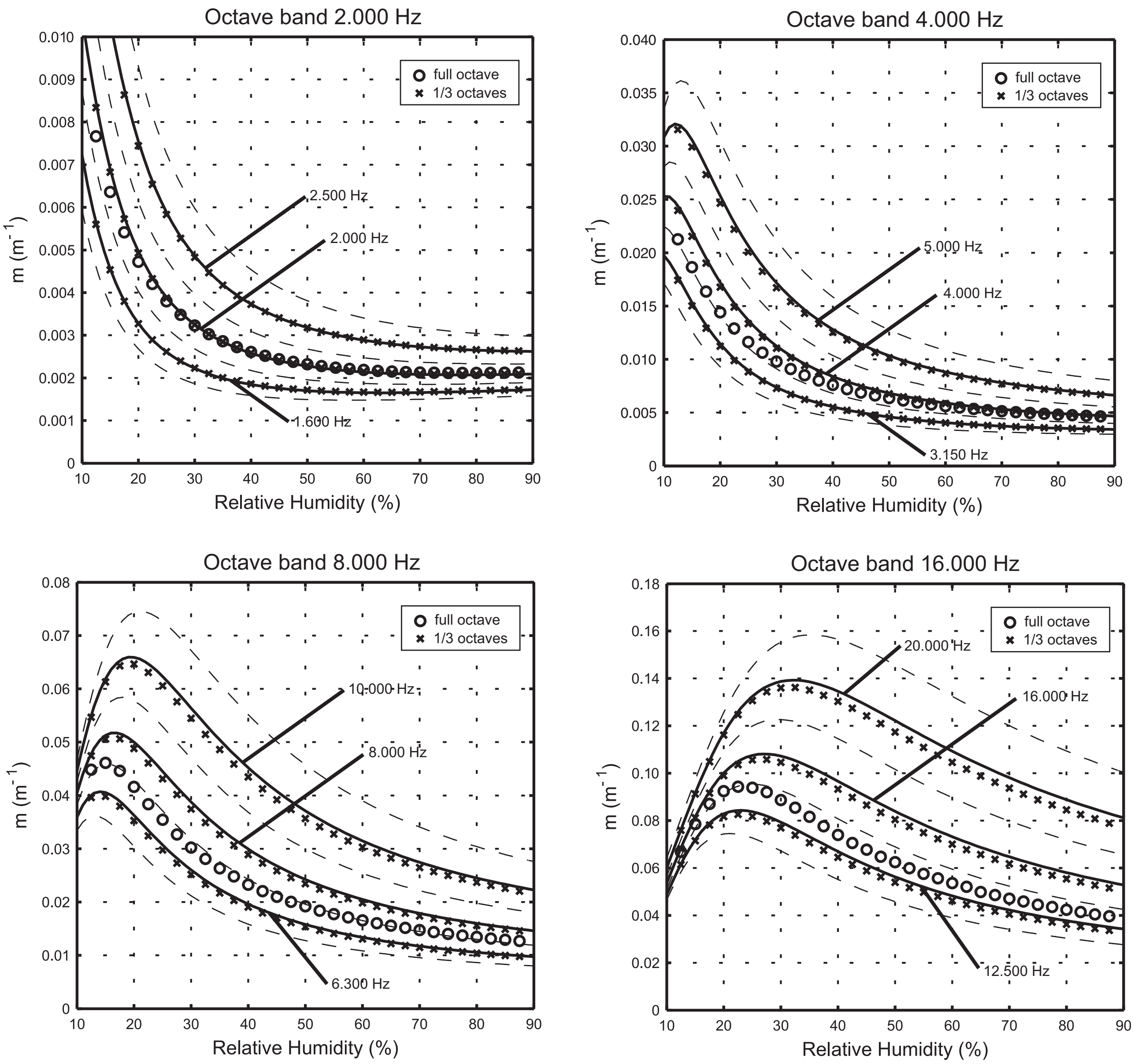

FIG. 3. In every subplot, $m_{B;\mathrm{eff}}$ is presented for the three 1/3-octave bands and the full octave band, based on calculations using Eq. (7), Eq. (9) and ISO 3382 (Ref. 17). The calculated results for $m_{B;\mathrm{eff}}$ for the three 1/3-octave bands are represented by crosses and $m_{B;\mathrm{eff}}$ for the full octave band is represented by circles. Three solid lines represent the m_{center} for the center frequencies of the 1/3-octave bands based on the ANSI (Ref. 14) or ISO (Ref. 15) standards. The middle solid line also represents m for the center frequency of the corresponding full octave band. Four dashed lines represent m_{edge} for the edge frequencies of the 1/3-octave bands. The upper most and lower most dashed lines also represent the edge frequencies of the full octave band. Subplots (a)–(d) represent the full octave bands 2, 4, 8, and 16 kHz, respectively.

decline to zero, which is clearly erroneous. On the contrary, the summation method curves concave upwards approaching an asymptote, as expected. At infinite decay the ratio will approximate the ratio between the pure tone air attenuation at the middle frequency and lower edge frequency of the octave band. In Fig. 2(b), the ratio between $\delta L_B(f_k)$ and $\delta L(f_m)$ is presented for Temp = 10 °C and RH = 30%. Also, for this case, the summation method ratio is different for each octave band, caused by a different increase in the attenuation coefficient per frequency within each frequency band. So, it can be concluded that no fixed ratio is found between $\delta L_B(f_k)$ and $\delta L(f_m)$ for these cases. And, it can be concluded that for the application of calculating decay curves in full octave bands, the summation method works, while the approximation method fails.

B. Comparison of m_{center}, m_{edge}, and $m_{B;\mathrm{eff}}$ using the summation method

In this section, the air absorption for the center and edge pure tones within a frequency band, m_{center} and m_{edge}, calculated using the standardized models,[14,15] is compared to the effective air absorption coefficient, $m_{B;\mathrm{eff}}$, for 1/3-octave bands and full octave bands as calculated using the summation method Eqs. (7) and (9). Figure 3 shows graphs of the calculated intensity attenuation coefficient m_{center}, m_{edge}, and $m_{B;\mathrm{eff}}$ as a function of RH for the octave bands 2 4, 8, and 16 kHz. The temperature is fixed at 20 °C and $T_{\mathrm{w/o\_air\_abs}} = 2$ s. This situation could represent a typical concert hall, assuming that the amount of material sound absorption is equal in all octave bands, in this theoretical case even up to 16 kHz. As a result of the air absorption, the $T_{\text{with\_air\_abs}}$ would always be much lower than 2 s for the high frequency bands: Based on calculations using the summation method for the 16 kHz full octave band, $T_{\text{with\_air\_abs}}$ would only be 0.5 s. This is in line with actual measured T_{20} of 6 different concert halls for random climate conditions showing a range of 0.48 to 0.57 s.

In Fig. 3, it can be seen that for all four octave bands 2 to 16 kHz, $m_{B;\text{eff}}$ of the individual 1/3-octave bands is slightly lower than m_{center} using the center frequency of the 1/3-octave band. With a maximum error of 5% for the 1/3-octave bands up to 20 kHz, it can be concluded that the error is in the same order of magnitude as those presented by Sisler and Bass,[22] who found a maximum error of 1.1% up to 10 kHz. As the accuracy of the pure tone air absorption calculation model itself is 5%, it can be concluded that, for 1/3-octave band T_{20} estimations, using m_{center} is sufficiently accurate. However, the results show that the edge frequency method, where m_{edge} is used for 1/3-octave bands, does not hold as a rule of thumb for estimating 1/3-octave band $m_{B;\text{eff}}$ for T predictions.

For the full octave band 2 kHz, $m_{B;\text{eff}}$ of the octave band is close to m_{center}. However, for the 4, 8, and 16 kHz octave bands, $m_{B;\text{eff}}$ is clearly lower than m_{center}. With increasing octave band frequency, the difference between m_{center} and $m_{B;\text{eff}}$ becomes larger for the octave band. Note that the average of $m_{B;\text{eff}}$ for the individual 1/3-octave bands does not equal $m_{B;\text{eff}}$ for the full octave band. This shows that T_{20} averaged over three 1/3-octave band values is not equal to T_{20} derived from the full octave band containing those 1/3-octave bands.

C. $m_{B;\text{eff}}$ for variations in $t_{\text{w/o\_air\_abs}}$ and frequency spectra

The effect of using m_{center} instead of $m_{B;\text{eff}}$ on T is further investigated in this section for different reverberation times (without air absorption) and for different frequency spectra. This is done by determining the amount of overestimation in $T_{\text{with\_air\_abs}}$ by using m_{center} instead of $m_{B;\text{eff}}$ for the full octave band. The overestimation of $T_{\text{with\_air\_abs}}$ as a function of $T_{\text{w/o\_air\_abs}}$ is presented in Fig. 4 following

$$\text{overestimation} = -100 \times \left[\frac{T_{\text{with\_air\_abs}}(m_{\text{center}}) - T_{\text{with\_air\_abs}}(m_{B;\text{eff}})}{T_{\text{with\_air\_abs}}(m_{B;\text{eff}})}\right], \tag{10}$$

with $T_{\text{w/o\_air\_abs}}$ ranging from 0.5 to 8 s for a fixed Temp of 20 °C and RH of 50 for an initial sound intensity *I(0)* with 3 different frequency spectra: White noise (i.e., a 3 dB increase per octave), pink noise (i.e., a 0 dB increase per octave), and brown noise (i.e., a 3 dB decrease per octave).

The results show that, in general, the overestimation by using the pure tone method increases with the octave band frequency but also increases with the $T_{\text{w/o\_air\_abs}}$. Also, the overestimation increases with increasing frequency roll-off of the magnitude of the spectrum.

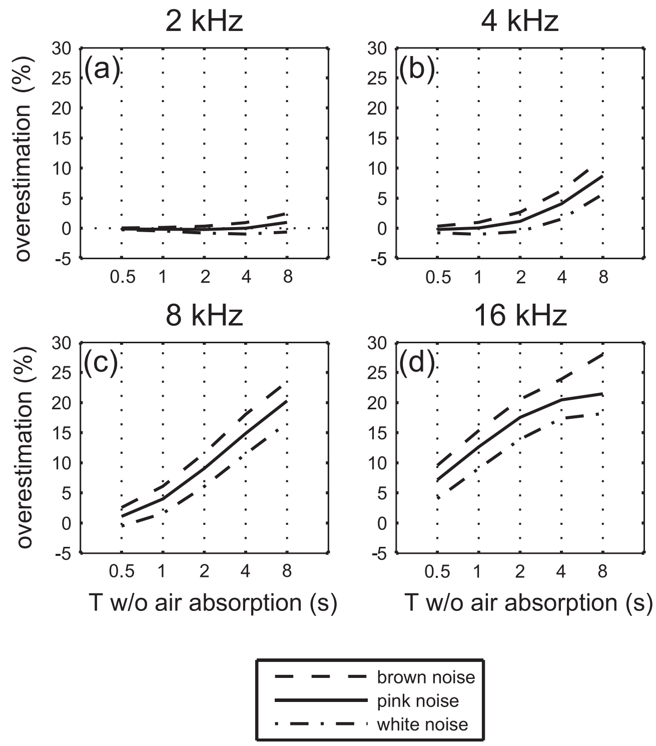

FIG. 4. The overestimation of $T_{\text{with\_air\_abs}}$ by using m_{center} instead of $m_{B;\text{eff}}$ for the full octave band, as a function of $T_{\text{w/o\_air\_abs}}$ for a fixed Temp of 20 °C and RH of 50, and for an initial sound intensity $I(0)$ with 3 different frequency spectra: White noise, pink noise, and brown noise. Subplots (a)–(d) represent the full octave bands 2, 4, 8, and 16 kHz, respectively.

IV. GUIDELINES AND APPLICATIONS

A. Accuracy of *T* calculations

For judging the necessary accuracy of T calculations, it is common to use the Just Noticeable Differences (JND). The JND for reverberation time T is not described in ISO 3382, however, a 5% JND has been reported as reasonable value for T.[27] Based on the findings in Sec. III, we can conclude that, for the octave band 2 kHz with a $T_{\text{w/o\_air\_abs}}$ up to 8 s and for the octave band 4 kHz for rooms with a $T_{\text{w/o\_air\_abs}}$ up to 2 s, the error in T_{20}, when using the pure tone center frequency for estimating m, is below 5% (within the JND). However, for the octave bands 8 and 16 kHz, the error of 5% in T_{20} is exceeded in most cases. So, for accurate T_{20} predictions at very high octave bands, it is recommended to take into account the effect of band limiting. It should be noted that the results are based on T_{20}, diffuse field conditions, and equal material absorption within the band. Because of the concave curvature of the decay, the results will be somewhat different for other evaluation ranges. For T_{30}, it was found that $m_{B;\text{eff}}$ can be maximum 5% lower than $m_{B;\text{eff}}$ for T_{20} in the above-mentioned ambient conditions.

B. Decay curve averaging

When using the summation method, a number of 96 averages over the octave band, as used in the analyses in Sec. III, might not always be necessary. An error analysis was performed for the Temp range 10 °C–30 °C and RH range 10%–90%, octave bands 2 to 16 kHz, for all three types of spectra used in Sec. III C, for both parameters T_{20} and T_{30} and for $N = 3$, 7, 12, 24, 48, and 96. It can be concluded that the error of 5% in reverberation time estimation is not exceeded when the average octave band decay curve is determined using the summation method with only three frequencies ($N = 3$), using the three center frequencies of each 1/3-octave bands within the full octave band. But it should be noted that the error increases with the amount of averages $N = 7$ or 12, and is only reduced again if $N = 24$, 48, or 96.

C. Practical values for predicting common cases

Figure 5 shows the derived $m_{B;\mathrm{eff}}$ and m_{center} for the octave bands 2, 4, 8, and 16 kHz for the three frequency spectra white noise, pink noise, and brown noise (using $N = 96$). The pure tone value for the mid frequency of the band m_{center} is added to illustrate the different result for the pure tone and summation method. Tables I and II give the values for $m_{B;\mathrm{eff}}$ for T_{20} and T_{30} calculations, respectively, for the case of a pink noise spectrum and ambient conditions Temp = 20 °C and RH = 50%. The presented values can be used to estimate T using statistical reverberation time models, like Sabine's or Eyring's equation, for various rooms under ambient conditions Temp = 20 °C and RH = 50%.

D. Application and limitations to the prediction models

The above-mentioned guidelines can be used in statistical calculation models like Sabine and Eyring to estimate reverberation time T_{20} and T_{30} in diffuse sound fields. It should be noted that, in practice, most rooms cannot fulfil the diffuse field requirement and other simulation methods might need to be used complementary to the statistical calculation models. However, there is little agreement on which model might be most accurate.[28–30] The summation method could also be used for geometrical room acoustic prediction models, e.g., the image-source method or ray-tracing, to determine the decay of the sound ray or particle due to air absorption. In this way, the concave shape of the decay curve could be taken into account. Such model could even be used to study the impact of air absorption in octave bands for non-diffuse sound fields.

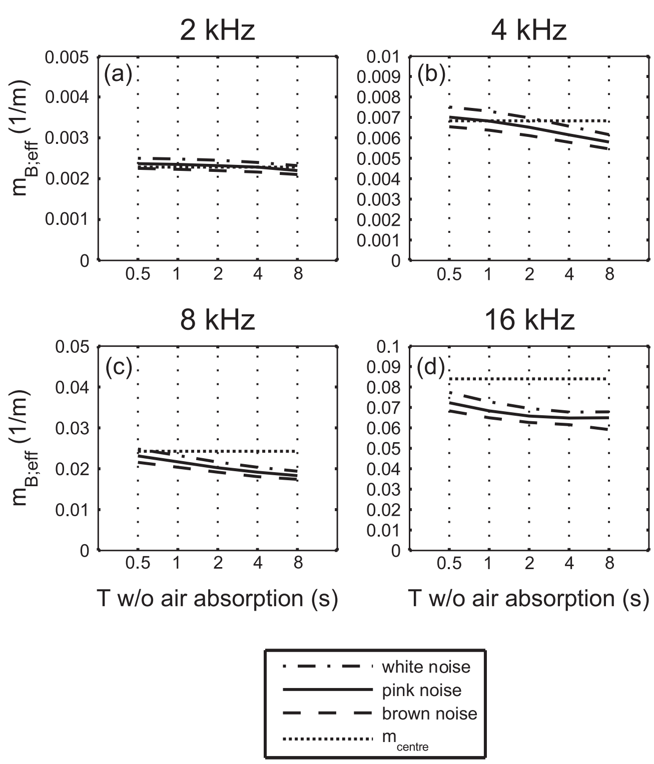

FIG. 5. $m_{B;\mathrm{eff}}$ and m_{center} for the full octave band, as a function of $T_{\mathrm{w/o\_air\_abs}}$ for a fixed Temp of 20 °C and RH of 50, and for an initial sound intensity $I(0)$ with 3 different frequency spectra: White noise, pink noise, and brown noise. Subplots (a)–(d) represent the full octave bands 2, 4, 8, and 16 kHz, respectively.

TABLE I. Intensity attenuation coefficient $m_{B;\mathrm{eff}}$ for predicting T_{20} in octave bands for different reverberation times without air absorption ($T_{\mathrm{w/o\_air\_abs}}$) for a pink noise spectrum, Temp = 20 °C, RH = 50%, and calculated using the summation method for $N = 96$.

	Intensity attenuation coefficient m for octave bands [1/m]			
$T_{\mathrm{w/o\_air\_abs}}$ [s]	2000 Hz	4000 Hz	8000 Hz	16 000 Hz
0,5	0.0024	0.0070	0.0231	0.0722
1	0.0024	0.0068	0.0217	0.0683
2	0.0023	0.0065	0.0202	0.0657
4	0.0023	0.0061	0.0191	0.0647
8	0.0022	0.0058	0.0183	0.0649

E. Correction of decay curves measured in a scale model

Decay curves measured in a physical scale model can be corrected for air absorption mathematically. It is possible to study the accuracy of correction for air absorption by the use of the summation method as presented in Sec. II A. A simulated "decay curve, measured in a scale model," I_{scale}, can be calculated using Eq. (7), $N = 96$ for the full octave band, a scaled time, t_{scale}, and scaled $T_{\mathrm{w/o\_air\_abs}}$. This energy decay curve I_{scale} can be corrected for air absorption and scaled to the "real scale" energy decay curve by

$$I_{\mathrm{real}}(t_{\mathrm{real}}) = I_{\mathrm{scale}}(t_{\mathrm{scale}}) \cdot \frac{\exp(-ct_{\mathrm{real}}m_{\mathrm{real}})}{\exp(-ct_{\mathrm{scale}}m_{\mathrm{scale}})}. \tag{11}$$

From the real scale decay curve, I_{real}, the reverberation time can be determined and compared to the expected reverberation time (this is possible because $T_{\mathrm{w/o\_air\_abs}}$ is known).

TABLE II. Intensity attenuation coefficient $m_{B;\mathrm{eff}}$ for predicting T_{30} in octave bands for different reverberation times without air absorption ($T_{\mathrm{w/o\_air\_abs}}$) for a pink noise spectrum, Temp = 20 °C, RH = 50%, and calculated using the summation method for $N = 96$.

	Intensity attenuation coefficient m for octave bands [1/m]			
$T_{\mathrm{w/o\_air\_abs}}$ [s]	2000 Hz	4000 Hz	8000 Hz	16 000 Hz
0,5	0,0024	0.0069	0.0224	0.0687
1	0.0023	0.0067	0.0206	0.0646
2	0.0023	0.0063	0.0191	0.0617
4	0.0022	0.0059	0.0179	0.0608
8	0.0022	0.0055	0.0172	0.0603

Remember that the simulated decay curve I_{scale} is a summation of 96 decay curves, each having a distinct air absorption coefficient per pure tone frequency, while a single air absorption coefficient is used in the scaling process by Eq. (11).

An error analysis has been performed for ambient conditions Temp = 20 °C, RH = 50%, $T_{w/o\_air\_abs} = 2$ s, scaling factors of 1:10 to 1:20, and a measurement frequency range up to the 64 kHz octave band. For infinite decaying curves, it was found that for 1/3-octave bands, a maximum error of 2% in reverberation time T_{20} is made in the correction process, while using m_{center} for m_{real} and m_{scale} in Eq. (11). For the full octave band, two different strategies have been tested. The first is directly using the full octave band decay curve and $m_{B;eff}$ for m_{real} and m_{scale} in Eq. (11), resulting in a maximum error of 8% in reverberation time T_{20}. A second strategy is to calculate the individual 1/3-octave band decay curves using m_{center} for m_{real} and m_{scale} in Eq. (11), and summing these three curves to obtain the full octave band decay curve. With this strategy, the maximum error in reverberation time T_{20} is only 2%, similar to the maximum error in the individual 1/3-octave bands.

In practice, however, the decay range of the measured decay curve will always be limited by the measurement system. The correction process following Eq. (11) should only be applied to the actual decay curve, while discarding the part that is influenced by the background noise (approximately at the cross point), as explained in Fig. 6. As a result of the correction process, the available decay range will be reduced with increasing frequency. This means that a higher decay range has to be achieved in the scale model, to be able to fulfill the required decay range to be able to calculate the reverberation time. As an example, in a 1:20 scale model, a measured decay range of 60 dB is needed at the 40 000 Hz octave band to be able to derive T_{20} at 2000 Hz with a 35 dB decay range.

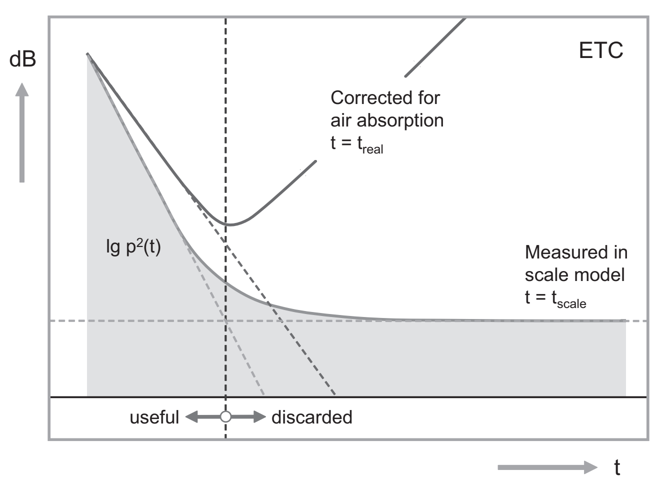

FIG. 6. An example of a decay curve, measured in a scale model, before and after correction for air absorption using Eq. (11). A relative time scale is used to be able to compare the decay curves. The noise tail in the measured decay curve is discarded from the measurement after air absorption correction. Note that the correction process will decrease the available decay range.

V. CONCLUSIONS

Air absorption is a function of frequency, but for calculations involving frequency bands, various methods have been proposed for the effective air absorption to employ. In this paper, these methods have been studied for their accuracy and the requirements to predict the reverberation time in diffuse field conditions within accuracy limits based on the JND.

For 1/3-octave bands up to 20 kHz and for $T = 0.5$ to 8 s and a spectrum equal to that of pink, white, or brown noise, it is found that the intensity attenuation coefficient can be estimated by the pure tone air absorption for the center frequency of the 1/3-octave band (m_{center}) with a maximum error in T of 5%. This 5% error is equal to the accuracy of the calculation model to predict the pure tone air absorption and the JND for reverberation time. So, it can be concluded that for 1/3-octave bands using m_{center} for predicting T is sufficiently accurate.

For full octave bands, it was concluded that the approximation method, as described in ANSI S1.26, fails to estimate the effect of air absorption on the energy decay in a diffuse field. The summation method as introduced in this paper that calculates the actual energy decay curves, was used to estimate the effect of air absorption when predicting reverberation time. Results of T calculations in octave bands have shown that, when estimating reverberation time at high frequencies ($f_{oct} \geq 8$ kHz), and/or very reverberant spaces ($T \geq 4$ s, regardless of their volume), it is recommended to take into account air absorption in octave bands using the summation method. For various practical cases, tables of values for $m_{B;eff}$ are presented that can be used for reverberation time calculations using statistical calculation methods, if results are to be compared to T_{20} or T_{30} measurements. For less reverberant spaces with $T \leq 2$ s and a frequency range up to 4 kHz, it is sufficiently accurate to use m_{center}, the center frequency of the full octave band. It should be noted that T_{20}, averaged over three 1/3-octave band values, is not the same as T_{20}, derived from the full octave band containing those 1/3-octave bands.

For the purpose of predicting reverberation time using a physical scale model within 5% error, the energy decay curve can be corrected for air absorption per 1/3-octave band using m_{center} as the air absorption coefficient. The full octave band decay curve can be constructed as a summation of the three corrected 1/3-octave band within the octave band.

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