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## Air Absorption Error in Room Acoustical Modeling

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Most statistical and ray-tracing computer models take into account the absorption of sound by air to estimate the reverberation time. Extensive research by many scientists lead to the standardized calculation model for pure tone air absorption. The phenomenon was discovered from a room acoustical point of view by Sabine, while the further development of the calculation model took place in the fields of physics and environmental noise. As a result, several parameters and units are used for the same phenomenon. However, air absorption is calculated for pure tones, while room acoustics calculations are performed in frequency bands. Most computer models use the centre-frequency of the normalised frequency bands to calculate the air absorption by the pure tone method. Reverberation measurements in frequency bands under laboratory and practical conditions show that errors larger than the Just Noticeable Difference result in calculating the air absorption by this ‘centre-frequency method’. No literature was found that provides an accurate air absorption calculation for frequency bands in relation to the reverberation time without the use of iteration. An existing rule of thumb is validated for application to room acoustics.

## 1 Introduction

### 1.1 Air absorption

It was Sabine [1] who in 1929 first noticed a variation in the reverberation time of an empty reverberation room in his laboratory, caused by different climate conditions. In 1931 Knudsen [2] proved that this effect was not caused by a change of absorption properties of the surface material, but by the change of absorption properties of the air, when temperature and humidity changes. Extensive research by many scientist lead to the standardized calculation model in ISO 9613-1 [3] and ANSI S1.26 [4] for pure tone air absorption based on sound decay measurements in reverberation rooms [1,2,5,6] and impedance tubes [7,8,9,10,11,12], with varying frequency range, gas mixtures and climate conditions. The final calculation model is presented in literature [13,14,15].

### 1.2 Room acoustical modeling

Nowadays, most statistical and ray-tracing calculation models, that predict room acoustical parameters like the reverberation time, take into account the air absorption as a correction factor  $4mV$  added to Sabine’s reverberation formula Eq.(1).

$$RT = 55,3 \frac{V}{c(A + 4mV)} \quad [s] \quad (1)$$

where,

- $RT$  = reverberation time [s]
- $V$  = room volume [ $m^3$ ]
- $c$  = speed of sound in air [m/s]
- $A$  = material absorption [ $m^2$ ]
- $m$  = intensity attenuation coefficient [ $m^{-1}$ ]

Most computer models use the centre-frequency of the normalised frequency bands to calculate the air absorption by the pure tone method. Frequency band reverberation measurements under laboratory and practical conditions show that errors larger than the JND are made in calculating the air absorption by this ‘centre-frequency method’. No literature was found that provides an accurate air absorption calculation for frequency bands in relation to the reverberation time without the use of iteration [16]. An existing rule of thumb is validated for application to room acoustics.

### 1.3 Names, parameters and units

Over time, the research point of view changed from room acoustics to the propagation of sound outdoors and high frequency transmission applications. This lead to different names for the same phenomenon, where the medium is often referred to as air or atmosphere and the process as absorption or attenuation. In combination with multiple grammatical structures, the four words resulted in up to twelve different names for the phenomenon. All possible combinations are expressed in table 1.

First part	Second part	Third part
absorption / attenuation	of sound by/in	air/ the atmosphere
air/atmospheric	absorption / attenuation	-

Table 1: Different names for the phenomenon.

The changes in research point of view also lead to the use of several parameters, units and parameter names for the same phenomenon, which makes the interpretation of literature difficult. An overview is presented in table 2.

Type of attenuation	Parameter	Unit	Parameter name
Intensity	$m$	$m^{-1}$ , $ft^{-1}$	Intensity attenuation coefficient Energy attenuation Air absorption factor
Pressure	$\alpha$ , $\mu$	Np/m, Np/100m, Np/km Np/ft, Np /100ft	Pressure attenuation coefficient Amplitude attenuation Air dissipation coefficient
Sound pressure level	$A$ , $\alpha$ , $a$ , $\Delta L$ $m$	dB/m, dB/100m, dB/km dB/ft, dB/100ft	Atmospheric attenuation coefficient Sound pressure level attenuation Air absorption coefficient Absorption coefficient

Table 2: Overview of parameters, units and parameter names

The three types of parameters with different units can be converted by Eq.(2) [17]. In this paper, the nomenclature are used as described in Eq.(2).

$$A = 10\lg(e) \cdot \alpha = 20\lg(e) \cdot m \quad (2)$$

where,

- A = atmospheric attenuation coefficient [dB/unit length]
- $\alpha$  = pressure attenuation coefficient [Np/unit length]
- m = intensity attenuation coefficient [unit length<sup>-1</sup>]

## 2 Frequency band calculations

### 2.1 Current methods

Modern acoustical measurement techniques and calculations make use of frequency bands instead of the pure tone method, which was used when developing and validating the model for air absorption calculation. For large propagation distances, atmospheric absorption shapes the spectrum [18]. This effect must be accounted for when predicting the air absorption in frequency band calculations. Some methods are described in ISO 9613-1 Annex D [3] and ANSI S1.26 Annex E [4]. In these methods the air absorption for frequency bands depends on the distance that the sound has travelled.

These methods are usable for the prediction of the attenuation of sound when propagating outdoors, but not for room acoustical calculations, when predicting parameters like the reverberation time (RT). Although the distance that the sound travels can be expressed by RT x speed of sound (as described in ANSI S1.26, par. 6.3 and [16]), the distance is still unknown when the RT is unknown. Hence, the RT can only be calculated by the use of iteration when calculating the air absorption for frequency bands by these methods [16,18]. A method without the use of iteration is desirable from a practical point of view.

### 2.2 Edge frequency method

The only frequency band air absorption calculation method that could be used for a practical prediction of the RT is *the edge frequency method* as first described in the standard ARP 866A [19] by Harris as a rule of thumb. According to this method, for third octave frequency bands  $f_c > 4\text{kHz}$  air absorption can be calculated using the lower edge frequency of the band in the pure tone method by Eq.(3).

$$A_{band}(f_m) = A_{pure}(f_L) \quad [\text{dB}] \quad (3)$$

where,

- $A_{band}$  = frequency band atmospheric attenuation coefficient [dB/unit length]
- $f_m$  = centre frequency of third octave band [Hz]
- $A_{pure}$  = pure tone atmospheric attenuation coefficient [dB/unit length]
- $f_L$  = lower-edge frequency of third octave band [Hz]

## 2.3 Edge frequency method and RT

The edge frequency method was developed from an environmental noise point of view and was only validated for the propagation of sound outdoors. To validate the edge frequency method for predicting the air absorption for room acoustical applications, over 3800 RT measurements have been performed by the author in a reverberant room while varying the temperature (Temp) in a range of 12°C to 38°C and the relative humidity (RH) in a range of 15% to 80%, see Fig.1. Also, the method has been validated for field measurements.

## 3 Measurements

### 3.1 Experimental setup

A standardized concrete constructed reverberation room is not climate controlled. Instead, a climate controllable room was used, as normally used for research on thermal comfort. The 175 m<sup>3</sup> room is finished by 1 mm thick aluminium panels on 100 mm EPS-foam. The average RT of the room is 1.7 seconds and the field was assumed to be diffuse enough for at least frequencies  $\geq 1\text{ kHz}$ , making the room suitable for the experiment. To avoid a change in tension in the panels due to temperature changes, all panels were screwed loose, hence making the material absorption independent of the temperature.

The climate was controlled by changing the water temperature inside tubes behind the panels in the walls, floor and ceiling, making it a well distributed heating and cooling system. The absolute humidity was controlled by a humidifier. A ventilator was used for mixing air during humidification. No air drying system was available.

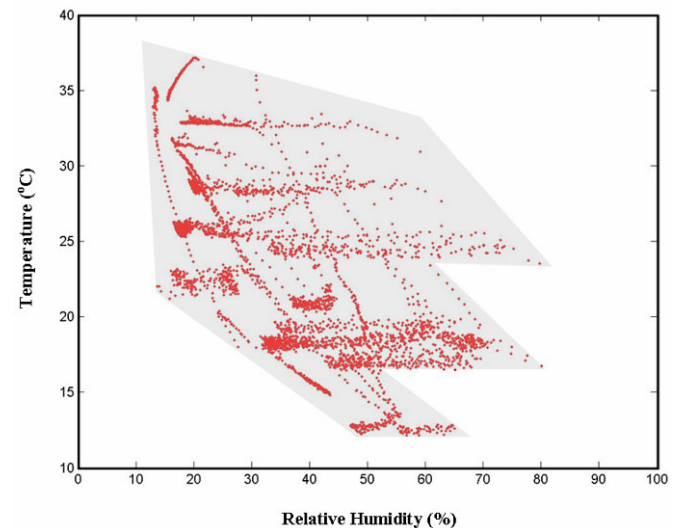


Fig.1: Distribution of measured Temp and RH.

The climate conditions inside the room were monitored every minute by calibrated sensors. Temp and RH were measured at 4 positions in the room and averaged. The wall surface temperatures were monitored to avoid condensation and the air pressure was measured. Also, the CO<sub>2</sub>-concentration in the air was measured, as CO<sub>2</sub> affects the speed of sound and also concentrations higher than 1000 ppm can affect the air absorption at high humidity's [13].

RT measurements were performed by the impulse response (IR) method using DIRAC 4.1 [20] on two computers. Four fixed microphone positions and two fixed loudspeaker positions were used. The computers were synchronized as to perform an IR measurement directly one after another, in pairs of one loudspeaker and two microphone positions, resulting in a total of 4 IR measurements within 22 seconds.

While varying the temperature or absolute humidity, the IR measurements were automatically performed and saved with an interval of 5 or 10 minutes by the use of the auto measure function. This made it possible to perform the measurements during the night, not disturbing the people working in the same building during daytime.

### 3.2 Relative octave band air absorption

The sound absorption of the room boundaries is hard to predict or to measure accurately. Also, a comparable room with a different volume was not available to determine the material absorption by the two-chamber method as proposed by Knudsen [21]. As a result, it was only possible to consider the differences in air absorption.

Most room acoustical modeling programs predict parameters in normalised octave frequency bands. For this reason all results are presented for full octave bands.

### 3.3 Calculations

For every measured IR the maximum decay range per frequency is determined by calculating the impulse to noise ratio (INR) [22]. The octave band reverberation time T20 was calculated when the decay range requirements of 35 dB were met. The data was added to the climate data matrix. Also, all data with a wall surface humidity of RH > 95% and an air CO<sub>2</sub>-concentration of < 1000 ppm are left out of the data. Fig.2 shows the minimum, maximum and distribution of all measured RT's in the octave bands 31.5 Hz to 16 kHz.

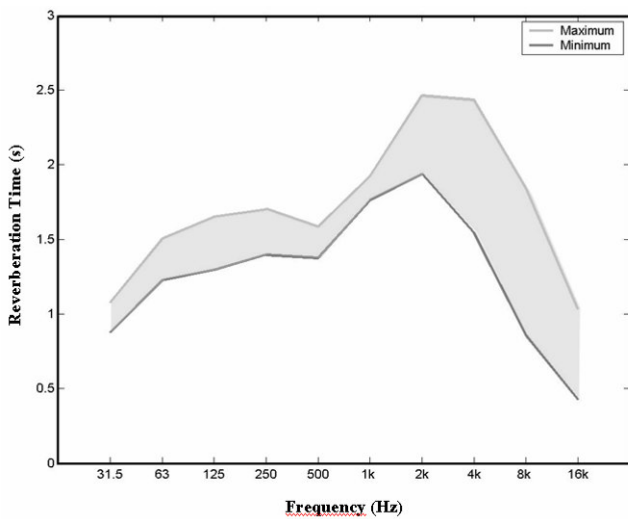


Fig.2: Distribution of measured RT.

From the measured RT, the intensity attenuation coefficient has been calculated by rewriting Eq.(1) to Eq.(4). The speed of sound in Eq(4) depends on the Temp, RH, air pressure and CO<sub>2</sub>-concentration and is calculated by Cramers model [23]. Then, the calculated  $m_{pa;rel;oct}$  was corrected for the

atmospheric pressure by Eq.(5). Finally, the relative octave band atmospheric attenuation coefficient  $A_{po;rel;oct}$  in dB/km is calculated by Eq.(2).

$$m_{rel;oct} = \frac{1}{4V} \left( \frac{55,3V}{cRT_{oct}} - A_{fit} \right) \quad [\text{m}^{-1}] \quad (4)$$

$$m_{p_0;rel;oct} = \frac{P_a}{P_0} m_{pa;rel;oct} \quad [\text{m}^{-1}] \quad (5)$$

where,

$RT_{oct}$  = reverberation time [s]

$V$  = room volume [ $\text{m}^3$ ]

$c$  = speed of sound [m/s]

$A_{fit}$  = estimated material absorption [ $\text{m}^2$ ]

$m_{pa;rel;oct}$  = relative octave band intensity atten. coeff. [ $\text{m}^{-1}$ ]

$P_a$  = atmospheric pressure [Pa]

$P_0$  = reference atmospheric pressure of 101,325 Pa

$m_{p_0;rel;oct}$  = relative octave band intensity atten. coeff., corrected for atmospheric pressure [ $\text{m}^{-1}$ ]

The material absorption  $A_{fit}$  in Eq.(4) was estimated by curve-fitting the results to the ISO 9613-1 prediction model for the pure tone atmospheric attenuation coefficient calculated with the centre-frequency and the lower-edge-frequency of the octave band.

## 4 Results

### 4.1 Relative air absorption

For each of 10 octave bands and 6 groups of 5 °C wide Temp-ranges, the atmospheric attenuation coefficient is presented in a graph as function of the RH, as the variation in air absorption is mostly influenced by this parameter. When curve fitting to the centre-frequency and the lower-edge-frequency it resulted in a total of 120 graphs.

It was found that:

- for frequencies < 1kHz, no correlation exists between the change of RT and the change of climate conditions. The distribution of measured RT in this frequency range is probably caused by the non-diffuseness of the room at these frequencies (Fig.2).
- for frequencies 1 kHz and 2 kHz a good correlation exists when fitting the relative octave band air attenuation coefficient to the centre-frequency of the band.
- for frequencies > 4 kHz a good correlation exists when fitting the relative octave band air attenuation coefficient to the lower frequency of the band.

As an example, the graphs for Temp-range 20-25 °C and octave bands 2 and 4 kHz are presented in Fig.3 and Fig.4. Fig.3 shows the measurement results, fitted to the pure tone calculation for the centre-frequency of the band, Fig.4 as fitted to the pure tone calculation for the lower-edge-frequency of the band.

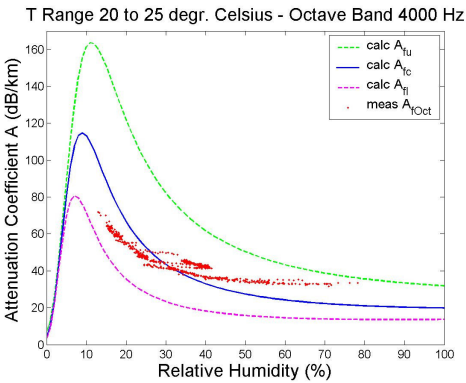
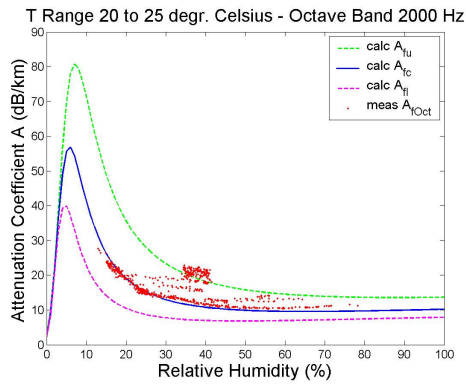


Fig.3: Centre-frequency curve fitting.

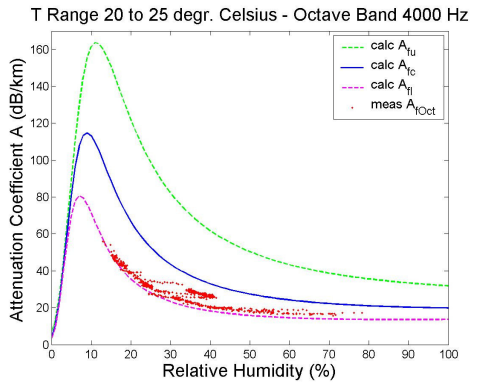
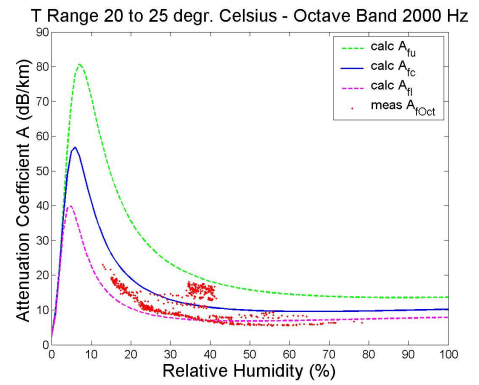


Fig.4: Lower-edge-frequency curve fitting.

## 4.2 Absolute air absorption

The graphs show that the *relative* octave band attenuation coefficients follow the trend of the pure tone calculations according to the edge frequency method. To further investigate if this is also valid for the *absolute* octave band atmospheric attenuation coefficient, the effect of narrowing the frequency bandwidth on the measured RT of a concrete constructed reverberation room is presented in Fig.5.

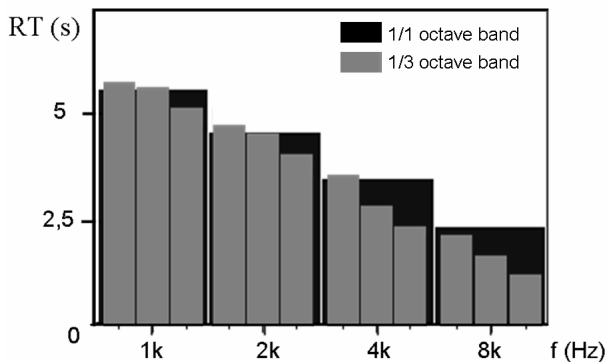


Fig.5: Effect of bandwidth on the calculated RT.

Fig 5 shows that:

- for frequencies 1 and 2 kHz the RT of the octave band almost equals the RT of its centre third octave band.
- for frequencies  $\geq 4$  kHz the RT of the octave band almost equals the RT of its lowest third octave band.
- for frequencies  $\geq 4$  kHz the difference between the RT of the lower and middle third octave band within an octave band is larger than the JND of 10%.

## 5 Conclusion

It is shown that:

- No literature has been found that provides an accurate frequency band air absorption calculation for predicting the reverberation time without the use of iteration.
- Due to the use of different names, parameters and units, literature must be interpreted carefully.
- The *edge frequency method* is an useful rule of thumb for calculating the octave band atmospheric attenuation coefficient within the JND for predicting the RT.

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