Room Acoustic Material Property Determination Using a Multi-Microphone Impedancetube

Bachelor Project ESD6

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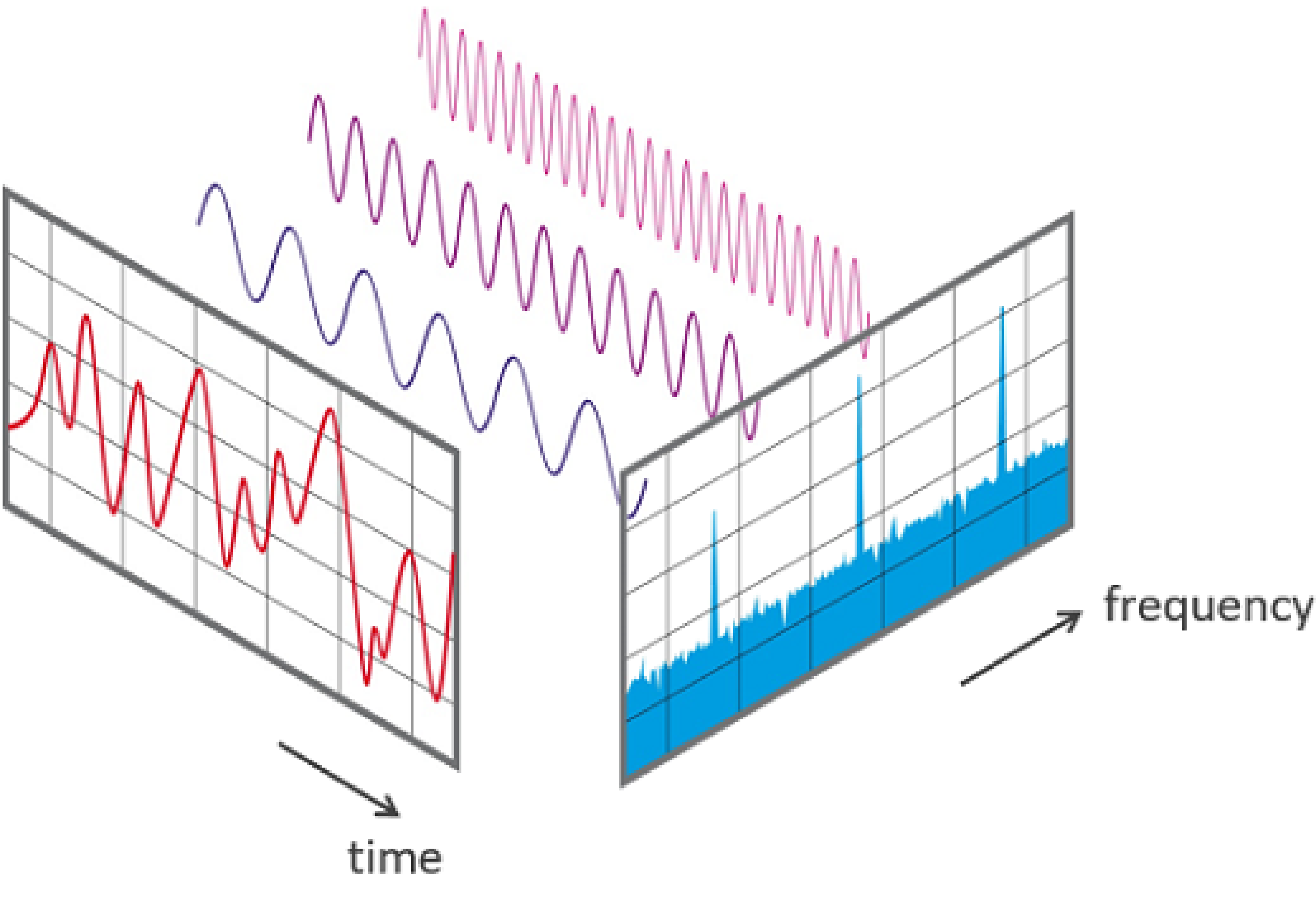

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Lorem Ipsum.

Contents

Preface

This report searches the requirements to develop an impedance tube based upon DS/EN ISO 10534-2:2023. In appendix B on page 28 all formulas and variables will be noted, in order of appearance.

Aalborg University, 18-12-2024

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1 Introduction

Acoustics are present in every aspect of life, no matter how small or large, resulting in acoustics significantly impacting the very perception of life. Scientific acoustical studies began emerging as far back as the 6th century BC with Greek philosophers and later Roman architects/engineers embracing acoustic properties in construction, [1]. However, the contemporary understanding of acoustics has only existed for approximately 200 years, [1]. Within those 200 years, acoustics has changed from a phenomenon only understood by scholars to an aspect of life, that most can relate to or know of to some degree.

In modern construction, acoustical properties have traversed from being reserved for performance centres, to being integrated into almost anything. It has become crucial for the average homeowner to achieve "good acoustics", along with acoustics occupying an increasingly large facet of large-scale construction. To achieve "good acoustics" a multitude of methods are available, ranging from adding a thick carpet or heavy drapes to bass-traps, vibration minimizing, and similar sound-deadening techniques.

Unfortunately, creating an acoustically perfect room is expensive, and in many cases wouldn't resemble a habitable room in common sense. Therefore the next-best option is adding unnoticeable elements such as padded furniture, rugs, pillows, drapes, and acoustic art/images or incorporating constructional options such as floor dampening, carpets, acoustic ceilings, and other, more intrusive options, [2, 3].

To bridge the gap between the historical and practical perspectives on acoustics, it is essential to consider the challenges and trade-offs involved in achieving optimal acoustical environments. While the importance of acoustics in everyday life and construction is evident, the practical implementation of "good acoustics" is often constrained by cost, aesthetics, and feasibility. This raises a fundamental question that initializes this project:

"How can "good acoustics" be defined and quantified in a way that balances theoretical ideals with real-world applicability?"

2 | Problem Analysis

2.1 Room Acoustics

Determining good acoustics is as subjective as determining which music is pleasant. While subjective qualities are present, objective aspects should be considered as well, as the very shape of a person (ears, head, shoulders, etc.) influence the perception of sound as well, [4, 5, 6, 7, 8]. Furthermore, good acoustical properties are not as "simple" as attempting to achieve anechoic conditions, as the inherent psychoacoustical properties of an anechoic room are not considered pleasant. Fortunately, guidelines exist for what is, in general, considered good acoustics. The metrics are room gain (G), reverberation time (RT60), early decay time (EDT), speech intelligibility (C50), definition (D50), musical clarity, and temporal distribution. The first four can be estimated by using the following:

G:
The gain of a room is very literally the amplification or attenuation that a room provides. It can be measured using a calibrated omnidirectional speaker (such as a dodecahedral speaker), where an impulse is first measured in free field (an anechoic room), and then in the room to be examined. The measurement in free field is done by measuring at a distance of 10 m from the sound source, and is repeated for at least 5 measurements at various locations to create an average, [9, 10]. As in free field, the room to measured should have an equal amount of measurements made. The gain of a room can be described with the following equations from DS 3382-1, [10]:

$$G = 10 * log10 \left(\frac{\int_0^\infty p^2(t)\,dt}{\int_0^\infty p_{10}^2(t)\,dt} \right) = L_{pE} - L_{pE,10} [dB] \tag{2.1}$$

$$L_{pE} = 10 * log10 \left[\frac{1}{T_0} * \int_0^\infty \frac{p^2(t)\,dt}{p_0^2} \right] [dB] \tag{2.2}$$

$$L_{pE,10} = 10 * log10 \left[\frac{1}{T_0} * \int_0^\infty \frac{p_{10}^2(t)\,dt}{p_0^2} \right] [dB] \tag{2.3}$$

Where: $p(t)$ is the instantaneous sound pressure of the impulse response measured at a point in the room, $p_{10}(t)$ is the instantaneous sound pressure of the impulse response measured at 10m in free field, p_0 is $20\mu Pa$, T_0 is 1 second, L_{pE} is the sound pressure exposure level of $p(t)$, and $L_{pE,10}$ is the sound pressure exposure level of $p_{10}(t)$.

If any of the rooms are not large enough to complete the measurements at 10 meters, they can instead be done at 3 meters and modified with:

$$L_{pE,10} = L_{pE,d} + 20 * log10(d/10) [dB] \tag{2.4}$$

Or even simpler by using, [9, 10]:

$$L_p = L_{p,10}[dB] \tag{2.5}$$

Where: L_p is the sound pressure level averaged across every measurement point and $L_{p,10}$ is the sound pressure level measured at 10 m in free field.

Alternatively if a sound source with known sound power level is available, the gain can be obtained by the following, [9, 10]:

$$G = L_p - L_W + 31dB \tag{2.6}$$

Where: L_p is the sound pressure level averaged across every measurement point and L_W is the sound power level of the sound source, and should be measured according to DS 3741.

RT60:
Reverberation **T**ime 60 describes the time it takes for sound a level to decay 60 dB. In many practical applications, background noise makes it difficult to measure a full 60 dB decay, and therefore, T20 or T30 is used instead. T20 and T30 differ from RT60 by measuring either 20 or 30 dB decay and following the description set in DS ISO 3382-2, the decay time must be measured from -5 to -2(3)5 dB, and not from 0 to -2(3)0 dB, [11, 9, 12, 13]. In figure 2.1a, an example of measuring T30 can be seen, where it should be noted that the decay is first measured from -5 dB. When using T20 or T30, the time measured should be multiplied by 3 or 2 to harmonize with RT60. It should furthermore be noted that T20 is most frequently used, as DS 3382-2 states that *"the subjective evaluation of reverberation is related to the early part of the decay"*, and that *"the signal-to-noise ratio is often a problem in field measurements, and it is often difficult or impossible to get a evaluation range of more than 20 dB."*, [11].

Sabine's equation for a diffuse sound field can be used to estimate a room's reverberation time. It takes the input V for the volume of the room in cubic meters, α for the absorption coefficient, and S for the surface area of the room in meters, and is used as:

$$RT60 = \frac{0.161 * V}{S_i * \alpha_i} \leftrightarrow RT = \frac{0.161 * V}{A} \tag{2.7}$$

Where:

$$A = \sum S_i * \alpha_i \tag{2.8}$$

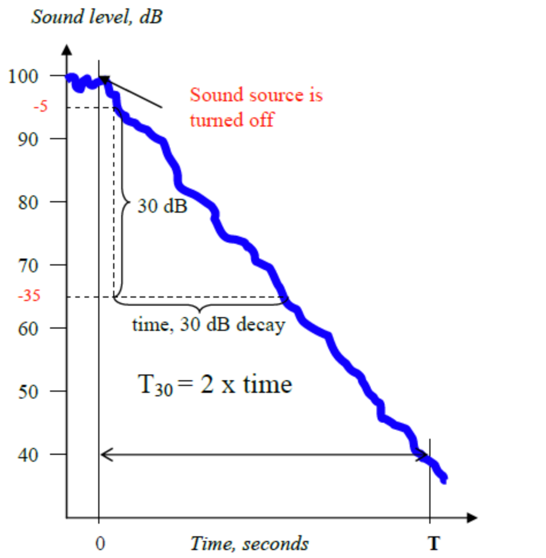
The reasoning behind equation 2.8/the lower fraction of 2.7 is to compensate for different materials with different absorption coefficients in a room. It should, however be denoted that since Sabine's formula assumes a diffuse sound field, it is best used concerning EDT rather than T30 or T20 due to the corresponding decay curves. This can be seen in figure 2.1b, where the solid straight line matches a continued approximation derived from the EDT. The dashed line is a more realistic decay curve of a room with absorbent materials, such as acoustic ceilings, [9].

In general, some optimal RT ranges are, [14, 15, 16, 9, 17]:

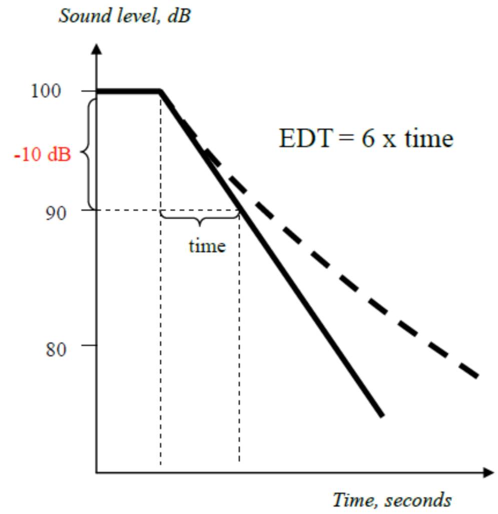
- Speech-oriented spaces, such as classrooms, meeting rooms, lecture halls, etc. require a short reverberation time of 0.3-1 second, to ensure speech intelligibility.
- Musical performance rooms, such as opera houses, concert halls, clubs, etc. would typically benefit from longer reverberation times, ranging from 1.5-3 seconds.

- Multi-use rooms such as dining halls, auditoriums, etc. benefit from a compromise, with reverberation times of 1.2-2 seconds.

- Sacred rooms/rooms of worship, such as churches, chapels, monasteries, etc. have much wider ranges, as they (dependent on religious purposes) have a reverberation time between 3-10 seconds.



(a) Definition of 30 dB decay (T30). Notice the timer starts at -5dB, [9].



(b) Illustration of EDT, [9].

Figure 2.1: T30 and EDT illustrations, [9].

EDT/T10:
Early decay time describes the first 10 dB decay within a room and is sometimes denoted T10, similarly to T20 and T30. The main difference from T20 and T30 is that EDT does not include the same -5 dB buffer but instead measures the actual first 10 dB decay. According to [9], [18] and DS 3382-1, [10], the EDT should be the subjectively most important reverberation characteristic when determining the acoustic properties of a room. EDT is determined by the first 10 dB of attenuation multiplied by 6 to reach a number comparative with RT60. The EDT equation is most beneficial when it comes to the psychoacoustic perception of a room and for determining "ideal" decay time, [18]. This is caused by the minimum of summed reflections present within the first 10 dB decay.

C50/C80:
To determine the clarity relation of a room as an acoustical parameter, C50 or C80 is used. C50 estimates the reflections and their energy present after 50 ms, while C80 estimates them after 80 ms. The idea is that reflections present after the critical time limit muddles perceived speech and reduce clarity. The critical time limit varies from person to person, with age, and is furthermore dependent on what exactly is being listened to, [9, 14, 15, 17, 10]. C50 is most often used for speech intelligibility and C80 is used for music clarity. The C50 and C80 relation is calculated by:

$$C50 = 10 * log10\left(\frac{Energy(0-50ms)}{Energy(51ms-end)}\right)[dB] \tag{2.9}$$

$$C80 = 10 * log10\left(\frac{Energy(0-80ms)}{Energy(81ms-end)}\right)[dB] \tag{2.10}$$

Where the "Energy" values are derived from a broadband impulse response in the room. The impulse response is recorded and divided into integrated squared energy values before and after the critical time limit, [9, 14, 15, 17, 10]. Both can also be found generally by:

$$C_{t_e} = 10 * log10\left(\frac{\int_0^{t_e} p^2(t)\,dt}{\int_{t_e}^{\infty} p^2(t)\,dt}\right)[dB] \tag{2.11}$$

Where: C_{t_e} is the early to late index. t_e is the early time limit (e.g. 50 or 80 ms) and $p(t)$ is the measured sound pressure of the impulse response, [10].

For speech clarity, values above 0 dB are considered good, while for music clarity it depends on music type and preference, but in most cases, a value between -2 dB and +4 dB is considered acceptable, [17].

D50:
Definition/Deutlichkeit after 50 ms is a percentage describing how many percent of the total energy is present within the first 50 ms. D50 is strongly correlated to C50, as D50 (and vice-versa C50) can be found by, [10]:

$$C50 = 10 * log10\left(\frac{D50}{1-D50}\right)[dB] \tag{2.12}$$

Or by itself using:

$$D50 = \frac{\int_0^{0.050} p^2(t)\,dt}{\int_0^{\infty} p^2(t)\,dt} \tag{2.13}$$

2.1.1 Introduction to sound

Now that the basic metrics for evaluating a room's acoustic properties have been established, sound as an entity can be determined. To do so, a lot of equations will be instantiated, with most coming from [7]. As most of the notation and equations in [7] are equal or at the very least similar to other sources, it has been chosen as the main source for equations, meaning all formulas used here can be found in [7] as well, unless otherwise noted. Other sources used for mathematical formulas are [4, 5, 6, 8, 10, 14, 15, 16, 19, 20, 21, 22, 23, 24, 25, 26]. For the time being, only ideal sound will be described, assuming no losses in propagation or obstacles. Furthermore, the medium is considered homogeneous and at rest, making the velocity of sound constant in relation to space and time. If the medium were air, the velocity is given by:

$$c = 331.4 + 0.6 * T\left[\frac{m}{s}\right] \tag{2.14}$$

With T being the temperature in degrees centigrade. C is set to be 343m/s for all following computations, based on an average temperature of 23.2 degrees. The average is used as exact calculations would require infinitesimal precision and, in practice, would be impossible to compute. An example could be a sports hall, wherein the temperature around players and audience is higher than under the rafters, [4, 5, 7, 14].

Another fundamental equation is the wave equation. The wave equation describes how sound propagates over time and space relative to the speed of sound. It is given by:

$$c^2 \Delta p = \frac{\partial^2 p}{\partial t^2} \tag{2.15}$$

where the squared speed of sound is defined by:

$$c^2 = \kappa \frac{p_0}{\rho_0} \tag{2.16}$$

in these equations, p is the sound pressure, rho_0 is the static gas density value ($\approx 1.2[\frac{kg}{m^3}]$, p_0 is the static sound pressure (measured in Pascal, where 1 $Pascal = 1\frac{kg}{m*s^2}$, and κ is the adiabatic component (for air $\kappa = 1.4$), [7]. In cartesian coordinates, the laplacian operator Δ is given by:

$$\Delta p = \frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} \tag{2.17}$$

To elaborate, the wave equation is derived from the conservation of momentum relation:

$$grad\ p = -\rho_0 * \frac{\partial v}{\partial t} \tag{2.18}$$

with its one-dimensional version being:

$$\frac{\partial p}{\partial x} = -\rho_0 \frac{\partial v_x}{\partial t} \tag{2.19}$$

where: v is a vector representing particle velocity, and t is time. Furthermore, the mass conservation requirement leads to:

$$\rho_0\ div\ v = -\frac{\partial \rho}{\partial t} \tag{2.20}$$

with ρ being the variable gas density. It is generally assumed that the variation in gas pressure and density is small compared to their static values. All of the above can be related by:

$$\frac{p}{p_0} = \kappa \frac{\rho}{\rho_0} = \frac{\kappa}{\kappa - 1} * \frac{\delta * T}{T + 273} \tag{2.21}$$

By eliminating the particle velocity v and variable gas density ρ from equations 2.18-2.21 one would arrive at the wave equation given in equation 2.15. The wave equation holds true for sound waves in any lossless fluid and for the resulting pressure, density, and temperature variations

Plane Waves

A plane wave simply put is a fraction of a spherical wave small enough that it can be assumed to have no curvature, [11, 10, 19, 20, 4, 5, 7, 8]. Another physical assumption that can be made, is that if a sound wave is present within a tube, with a diameter/height/width significantly smaller than the wavelength of said wave, it can be assumed to be planar, see section 3.2 on page 3.2 for more. It is effectively an orthogonal plane to a vector in a cartesian coordinate system. If that vector is equal to the x-axis, a plane wave can be described by the wave equation (2.15) with:

$$c^2 \frac{\partial^2 p}{\partial x^2} = \frac{\partial^2 p}{\partial t^2} \tag{2.22}$$

With a corresponding general solution given by:

$$p(x,t) = F(c * t - x) + G(c * t + x) \tag{2.23}$$

In equation 2.23 the first term represents a plane wave propagating positively along the x-axis and the second term a negative direction. From equations 2.22 and 2.23 it can also be seen that a constant pressure level is present at each wavefront. By specifying F and G as exponential functions including the imaginary components, the propagation is given as:

$$p(x,t) = \hat{p} * e^{i*k*(c*t-x)} = \hat{p} * e^{i*(\omega*t-k*x)} \tag{2.24}$$

Where $\hat{p}$ is amplitude, k is the propagation constant $k = \frac{\omega}{c}$, ω is the angular frequency, which can be used to obtain the temporal period $T = \frac{2*\pi}{\omega}$. This all connects to several interpretations of the wavelength formula:

$$\lambda = \frac{2*\pi}{k} \leftrightarrow \frac{2*\pi}{\frac{\omega}{c}} \leftrightarrow \frac{2*\pi*c}{\omega} \leftrightarrow \frac{c}{\frac{\omega}{2*\pi}} \leftrightarrow \frac{c}{f} \tag{2.25}$$

Now that amplitude, wavelength, and direction are known, the only missing parameters for expressing the plane wave are frequency and intensity. The frequency is given by $f = \frac{\omega}{2*\pi} * \frac{1}{T}$ with the unit Hz. If equation 2.18 is applied to equation 2.23, the only non-vanishing point of the wave is parallel to the x-axis, meaning that sound behaves as longitudinal waves in fluids, and the particle velocity can be found by:

$$v(x,t) = \frac{1}{\rho_0 * c}[F(c * t - x) - G(c * t + x)] \tag{2.26}$$

To obtain the ratio between sound pressure and particle velocity, also known as the characteristic impedance of a medium, the following is used:

$$\frac{p}{v} = \rho_0 * c \tag{2.27}$$

With $\rho_0 * c$ found by table values for ρ_0 and c in the correct medium. For air, the characteristic impedance is:

$$\rho_{0_{air}} * c_{air} = 1.2 \left[\frac{kg}{m^3}\right] * 343 \left[\frac{m}{s}\right] = 414 \left[\frac{kg}{m^2 s}\right] \tag{2.28}$$

Understanding the above relation makes it possible to determine the intensity of each wave. The plane imagined to be orthogonal to the x-axis will have energy present across its entire surface, and the average (denoted by the bar notation) product of the pressure and particle velocity on the surface yields the intensity:

$$I = \bar{pv} = \frac{\bar{p^2}}{\rho_0 * c} \tag{2.29}$$

To find the energy density of a wave, equation 2.30 is used:

$$w = \frac{I}{c} = \frac{\bar{p^2}}{\rho_0 * c^2} \tag{2.30}$$

And with that, sufficient information should be available to describe any plane wave.

Spherical Waves

Propagation in free air

Human Hearing and Perception

Loudness Sone Phone Fletcher Munson

2.1.2 Sound in Front of a Wall

Directly in front

Reflection at Normal Incidence

Reflection at Oblique Incidence

2.1.3 Closed Space Sound Field

2.1.4 Room Geometry in Relation to Acoustics

Design Considerations

Reflection of Sound

Sound Decay and Reverberation

2.1.5 Sound Absorbers

Absorbers in Construction

Absorbers in Furnishment

2.1.6 Measuring Techniques

Impulse Response of a Room

Acoustical Properties of Materials

skal være segway til impulsrør og teknisk analyse

2.2 Existing Solutions For Determining Acoustics

2.2.1 Impulse Response of a Room

2.2.2 Impedance Tube

2.3 Problem Statement

Noget a la:

"How can a square impedancetube capable of measuring very low frequency properties of construction materials be developed?"

3 | Technical Analysis

In an effort to analyze the technical needs of the project, the demands set for a prototype have been revisited. This identified the following areas of interest:

3.1 Reverberation Room Method

3.2 Standing Wave Method

[19]

3.3 Multi Microphone Method

[20]

3.4 Signal Processing Algorithm

4 | Demand Specification

4.1 High Level Specification

4.2 Demands Set by AAU

4.3 Functional Specification

5 System Design

5.1 Establishing an Algorithm

Specifikationer så som:

- Maximum Length Sequence
- Fixed point

Forklaring af algoritme - formål
Gennemgang af matematik
Gennemgang af kode
valg af enhed til at køre algoritmen - fordele, ulemper og constraints
Test af algoritmen på kendte signaler

5.2 Physical Setup

Størrelse på rør i forhold til sample sizes - eventuelt gennemgang af begrænsninger

Udforsk betydning af firkantet rør kontra rundt - fiberline rør måske? https://fiberline.com/da/produ
x-100-x-6-mm-060280

Afstande på rør

Elektrisk opsætning/valg af speaker, mic, amp osv

6 Integration

7 Acceptance test

General acceptance test

Sammenligningstest med Bruel og Kjær 4002 Standbølge Apparat af forskellige materialer.

8 Discussion

9 | Conclusion

"?"

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Glossary

C50 Clarity 50 ms. 2, 4, 5

C80 Clarity 80 ms. 4

D50 Definition 50 ms. 2, 5

EDT Early Decay Time. 2–4

RT60 Reverberation Time 60 dB. 2–4

T10 Reverberation Time 10 dB. 4

T20 Reverberation Time 20 dB. 3, 4

T30 Reverberation Time 30 dB. 3, 4

A | Appendix

B Mathematical Notations

B.1 Variables

$p(t)$ is the instantaneous sound pressure of the impulse response measured at a point in the room.
$p_{10}(t)$ is the instantaneous sound pressure of the impulse response measured at 10m in free field.
p_0 is $20\mu Pa$.
T_0 is 1 second.
L_{pE} is the sound pressure exposure level of $p(t)$.
$L_{pE,10}$ is the sound pressure exposure level of $p_{10}(t)$.
L_p is the sound pressure level averaged across every measurement point.
$L_{p,10}$ is the sound pressure level measured at 10 m in free field.
L_p is the sound pressure level averaged across every measurement point.
L_W is the sound power level of the sound source, and should be measured according to DS 3741.
$A = \sum S_i * \alpha_i$.
C_{t_e} is the early to late index.
t_e is the early time limit (e.g. 50 or 80 ms).
$p(t)$ is the measured sound pressure of the impulse response.
$c^2 = \kappa \frac{p_0}{\rho_0}$.
p is the sound pressure.
ρ_0 is the static gas density value ($\approx 1.2[\frac{kg}{m^3}]$ for air).
p_0 is the static sound pressure (measured in Pascal, where $1\ Pascal = 1\frac{kg}{m*s^2}$.
κ is the adiabatic component.

B.2 Formulas

$$G = 10 * log10 \left(\frac{\int_0^\infty p^2(t)\, dt}{\int_0^\infty p_{10}^2(t)\, dt} \right) = L_{pE} - L_{pE,10}[dB] \tag{B.1}$$

$$L_{pE} = 10 * log10 \left[\frac{1}{T_0} * \int_0^\infty \frac{p^2(t)\, dt}{p_0^2} \right] [dB] \tag{B.2}$$

$$L_{pE,10} = 10 * log10 \left[\frac{1}{T_0} * \int_0^\infty \frac{p_{10}^2(t)\, dt}{p_0^2} \right] [dB] \tag{B.3}$$

$$L_{pE,10} = L_{pE,d} + 20 * log10(d/10)[dB] \tag{B.4}$$

$$L_p = L_{p,10}[dB] \tag{B.5}$$

$$G = L_p - L_W + 31dB \tag{B.6}$$

$$RT60 = \frac{0.161 * V}{S_i * \alpha_i} \leftrightarrow RT = \frac{0.161 * V}{A} \tag{B.7}$$

$$A = \sum S_i * \alpha_i \tag{B.8}$$

$$C50 = 10 * log10\left(\frac{Energy(0-50ms)}{Energy(51ms-end)}\right)[dB] \tag{B.9}$$

$$C80 = 10 * log10\left(\frac{Energy(0-80ms)}{Energy(81ms-end)}\right)[dB] \tag{B.10}$$

$$C_{t_e} = 10 * log10\left(\frac{\int_0^{t_e} p^2(t)\,dt}{\int_{t_e}^{\infty} p^2(t)\,dt}\right)[dB] \tag{B.11}$$

$$C50 = 10 * log10\left(\frac{D50}{1-D50}\right)[dB] \tag{B.12}$$

$$D50 = \frac{\int_0^{0.050} p^2(t)\,dt}{\int_0^{\infty} p^2(t)\,dt} \tag{B.13}$$

$$c = 331.4 + 0.6 * T[\frac{m}{s}] \tag{B.14}$$

$$c^2 \Delta p = \frac{\partial^2 p}{\partial t^2} \tag{B.15}$$

$$c^2 = \kappa \frac{p_0}{\rho_0} \tag{B.16}$$

$$\Delta p = \frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} \tag{B.17}$$