Artistic aspects of architectural sound

(Konstnärliga aspekter av arkitektoniskt ljud)

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2018

AAHM01: Examensarbete i arkitektur/Degree Project in Architecture; LTH

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Supported by Saint-Gobain Ecophon AB

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Introduction

Sound in architecture has long been treated as a mere technicality and dismissed to the late stages of the design process. Instead of working with the acoustics early on, an acoustician is engaged as late as possible and assigned the task of "fixing" the problems that have been created earlier on. Architects rarely talk about acoustics as part of the aesthetic expression, or even as a matter of user comfort. Why is this? Is it because the physics behind soundwaves aren't properly understood? My theory is that the problem has its roots in the lack of a language to describe sound of different character and quality. We have a language for light, materiality, shape, proportion and all other architectural aspects that we can regard with our eyes. We believe that images are precise and that we all "know what we're talking about" when we look at the same image. (Whether this is the case will be discussed by someone else.) An interesting exercise is to find a nice place in the city (or somewhere else) and listen to it with closed eyes. When the visual impressions are shut out, the brain moves its focus to the other senses: hearing, touch, scent and taste.

This thesis is a tentative experiment in the field of architectural language. What is sound in architecture and why aren't we talking about it? How can it be talked of? There seems to be no proper language for discussing architectural sound. A terminology exists in the field of music and it might be possible to adapt it to architectural use. As architects, we deal both with artistic expression and with the biological needs of humans (even if the latter is often neglected). Sound has to do with both. I will not discuss any art-theoretical aspects of sound here but merely point out that it has an aesthetic effect, whether we want it to or not. What the effect is will depend upon the room but ignoring it completely doesn't make it go away.

A person looking for "the ultimate sound" will find no trace of a description of it here. The perfect sound is whatever fulfils the practical needs of a space and is of good aesthetic quality in relation to the room in question.

Author's views

I started to learn about architecture at a time when my skills as a luthier were becoming significant. Lutherie is the art of building stringed musical instruments, in my case mostly acoustic guitars. I've noticed certain similarities between lutherie and architecture. First and foremost, they both require artistic sensibility as well as significant technical and practical knowledge. A luthier builds instruments for people to play on and the architect builds houses for people to live or work in. In both cases the real magic comes after the process is finished.

Fig. 1. Luthier's workshop. Photo: Eric Bjerkborn.

I sometimes ask the question: "Is it possible to define architecture as the artistic and humanistic application of building technology?" This often seems to provoke architects and I'm still not quite sure why. It certainly isn't the whole truth but I believe that there is some relevance in it. I find that architecture has the power to make building technology meaningful; humane. A robot can build an artefact that looks like a guitar and makes guitar-like sounds but it takes a luthier to make it truly musical. Every instrument has its particular limitations and possibilities, just like every building project.

The type and quality of the wood used in a guitar will decide the character and colour of the tone while the balance, playability and musicality are the luthier's responsibility. A good way of showing this is by building a good guitar from very low-grade wood (which I have done). The architectural version of this is to build a pleasant building with very limited resources, which I've seen others do. The key in both cases is artistic flexibility and knowing how to work with the available materials. Not all possible things make sense. Not all things that would be meaningful are possible.

I often return to a Danish expression that is directly translated into "gives meaning" but is used like the English expression "makes sense". I like to ask things that I create: "Do you give meaning?". All art should give meaning in some way. If it doesn't, it's not art but simply there. In guitars, meaning usually comes in the form of musical inspiration and in architecture it comes from the users' experiences of the spaces as a setting of their daily lives.

My learning curve in room acoustics started when I attended a course at the department of Engineering Acoustics at LTH and a year later became intern at the R&D Department at Saint-Gobain Ecophon AB. Ecophon produces and sells room acoustics products, like ceilings and wall-mounted acoustic panels. My job was to research the effects of regulated diffusion, which means how sound can be made to bounce around the room in a controlled fashion, in relation to an acoustic ceiling. By learning about the inner workings of soundwaves, I unlocked a whole new world of architectural possibilities. By studying specific phenomena, I was able to devise some principles for how sound in rooms can be managed and how the "acoustic treatment" can be a part of the actual design. I got to understand the importance of acoustic ceilings and how incapable they are of solving all sonic problems that can spring up in closed spaces. This Masters' Thesis should be seen as the starting point of an endeavour to bring the sonic palette within the grasp of architects. It's not all about mathematics. Sound can, and should, be designed.

Fig. 2. Ecophons' office in Hyllinge. Photo: www.ecophon.se.

Sound and the architectural experience

It's been argued for decades that what we hear is as important as what we see when experiencing architecture. "Experiencing Architecture" is coincidentally the title of Steen Eiler Rasmussen's book from the late 1950s[1], in which he discusses many different ways of regarding architecture. The final chapter of the book argues that architecture can be heard despite not emitting any sound. The living world creates many different types of sounds and different rooms respond to these sounds in different ways. Imagine, for instance, playing a violin in a street, a field, a bedroom and a large public toilet. The sound from the violin will be the same but the sonic experience will vary radically because the rooms respond so differently. The toilet and the open field are the two extremes: one reflecting everything into reverberation and the other reflecting nothing at all. This is also why outdoor concerts rarely sound as good as indoor concerts.

Fig. 3. Picture borrowed from Adlibris.

In later years, one of the main advocates of the multisensory qualities of architecture has been the Finnish theoretician Juhani Pallasmaa. His book "The eyes of the skin – Architecture and the senses"[2] argues eloquently for the inclusion of all the senses in the architectural design process. If we assume for a moment, that architecture can be defined as space around people, it follows that it can't be fully experienced from a distance; from the outside. At the same time, we tend to back off to get a good overview. We regard things from afar because our eyes work that way – they have a limited width of vision; of the image they can take in at a time. We can't see through the backs of our heads. What architects seem prone to forget is that not all of our senses work this way. We can't touch things from further away than we can reach.

The connection between visual and tactile impressions is complex. If we remember what it's like to touch something, like a brick wall, our brain will associate the visual impression of a brick wall with

[1] (Rasmussen, 1964)
[2] (Pallasmaa, 2012)

that sensation. We don't need to actually touch the brick wall to get some measure of the feeling of roughness to our skin.

Pallasmaa also talks about how hearing and smell are senses that integrate us with our surroundings while vision is the sense of the solitary observer. He differentiates between peripheral vision and focused vision, where peripheral/unfocused vision is more including than focused vision.

The problem with Pallasmaa's book, like many other texts on architecture, is that it offers very little guidance to what an architecture for all the senses might look like, feel like or sound like. Pallasmaa talks about the "why" but not the "how".

Directional hearing

We can hear where sounds come from with excellent accuracy but it takes a lot of training to be able to "not hear" certain sounds. The brain has the ability to analyse the difference between the information it receives from the two ears and from it understand the space around it. In advanced simulation models, each unique listeners head is analysed to determine the so-called "Head-related transfer function" to allow the computer to reconstruct the process that the brain does all the time in teal-time. People who have an outer ear (cochlea) damaged often find it more difficult to tell where a sound is coming from than they did before their injury.

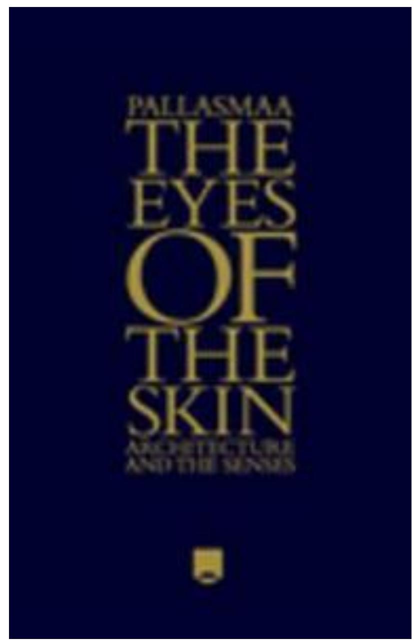

Fig. 4. Picture borrowed from Adlibris.

Just like our physical heads, our experiences of the sonic world around us are different. We also perceive sounds slightly differently, just like we do with colours. These things are studied under the heading "Psycho-acoustics". How does sound affect people – what they feel and what they do?

What we expect to hear

First of all, sound varies over time and with the season, just like light. When there's snow in the streets, the city sounds are muffled into a cosy and somewhat cushioned sensation. Birds don't normally sing in October, that's when the window panes are rattled by horizontal rain – at least in coastal regions. We also have different wishes at different times when it comes to the sounds around us. We're much less picky in our offices than in our bedrooms. Some sounds also belong in certain environments and can be extremely confusing when they appear in the "wrong" place. Imagine, for instance, that you place a filter coffee machine in the nave of a cathedral and plug it in. The bubbling sound would reverberate and give the idea of an enormous kitchen rather than a dignified religious building. Depending, of course, on the listeners' relationship to and feelings for the filter coffee machine.

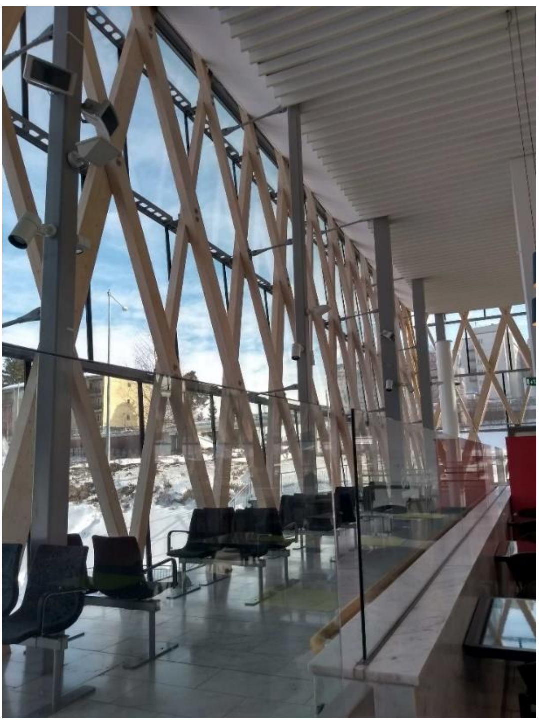

Fig. 5. Umeå bus station. The leaning wall directs sound upwards, the wood crosses diffuse (break) the sound and the ceiling absorbs sound. Photo: John Näsling.

Describing the qualities of architectural sound isn't as easy as describing, for example, wine. The problem is that there's no really agreed-upon language. Architectural sound could be described with words like: soft, sharp, boomy, clear, blurry, dry, metallic, crisp, enveloping and any number of others. Judging wine by its colour alone would in most cases be considered the height of superficiality. We want to know what the wine tastes like and what it smells like. How does it feel to the tongue? Does it compliment the food, if present? In the same way we shouldn't judge architecture by simply looking at it. We spend our days and years in architecture and should therefore worry more about how we feel within it than how it looks from a distance. Pallasmaa says that vision is the sense of the solitary observer while touch and hearing are the senses that make us feel included. We interact by talking and touching, at least as much as looking at each other. Shaking hands is how we greet each other, at the very least. While today's technology enables us to write to each other in real time, a hand-written letter can be smelt, touched, carried around in a pocket. It can be placed in a drawer to be found decades later and treasured as a memory of days long since passed. The words in themselves are only part of what makes it valuable, rather like finding 100 years of wall papers when renovating an old house. Physical traces to run your fingers over.

I've started by touching on, and will return to, the idea that architectural sound is an artistic aspect, rather than a technical subject. It needs to be addressed early in the process, indeed on the conceptual level, to avoid the clumsiness that appears when new designs are in reality retrofitted with acoustic ceilings and such to bring reverberation down to what is required by the standard. By defining some sort of sonic idea on the conceptual level, the technical installations can be made elegant and visually integrated into the design.

It has, at this point, become necessary to point out some more practical aspects of the acoustic properties of architectural spaces.

Fig. 6. Café Bryggan, noisy at lunch time. The sound reverberates between the walls, which are made of concrete and glass. Photo: www.bryggancafe.se

-"Excellent food and wine but talking was absolutely impossible."

My favourite example is the restaurant, where the following is all too common:

Most people go to restaurants both to eat and to spend time in conversation with friends, colleagues, spouses etc. Not being able to have an intelligible conversation is often a distinct problem and prevents many people from coming back to otherwise adequate establishments. That means fewer returning customers and less business than the place might otherwise have had.

The typical restaurant has a lot of sources of high-pitched noise, like the clatter of cutlery and clanking of plates, commotion from the kitchen and communication efforts from the guests. All these sounds are in a range of pitch that is near the point at which our ears are most sensitive. The clatter and clanking is very detrimental to our ability to hear speech properly. When one sound is used to hide or conceal another it's called "masking", in this case unwanted masking.

Sonic fashion

There's the branding aspect. Since the sound environment is instrumental to the character of a space, an establishment must decide which type of environment best suits their branding strategy. Should an atrium be spacious or cosy? Should a lobby convey a sense of calm or a sense of activity? What accent should the voice announcing floors in the lift use? These are questions for client and architect to decide, preferably together with an acoustician.

The word soundscape is popular today and is used to describe the sonic environment of a place. These are the sounds that shape the atmosphere and "tune" the place to the desired mood. Fountains on squares are as important to the soundscape as they are nice to look at. Removing the cars from a street means that all the "little" sounds can be heard, quite aside from there being no more cars to be run-over by.

Sound to "ordinary people"

We shall now leave the world of architecture for a moment and take a trip back in time, to England in the 1920's. The point of this little excursion is to show that sound matters to people outside the architectural community and therefore ought to matter to people within the architectural community. The buildings, rooms and places that we design are to be inhabited and used by mostly non-architects. Writers of novels of quality are aware of the importance of evoking different kinds of sensory experiences, to get their readers to feel connected to their characters (if that's what they want). The works I will refer to are "Lady Chatterley's Lover" by D.H. Lawrence and "Mrs. Dalloway" by Virginia Woolf. They were both written in the 1920's and they are both about people who remember the first world war. The wounds from the war are described in these books and one of the consequences appears to be an increased sensibility of the fragility of the world and the people who dwell in it. One of the purposes of architecture is to defend this fragility in a world otherwise driven by economic interests.

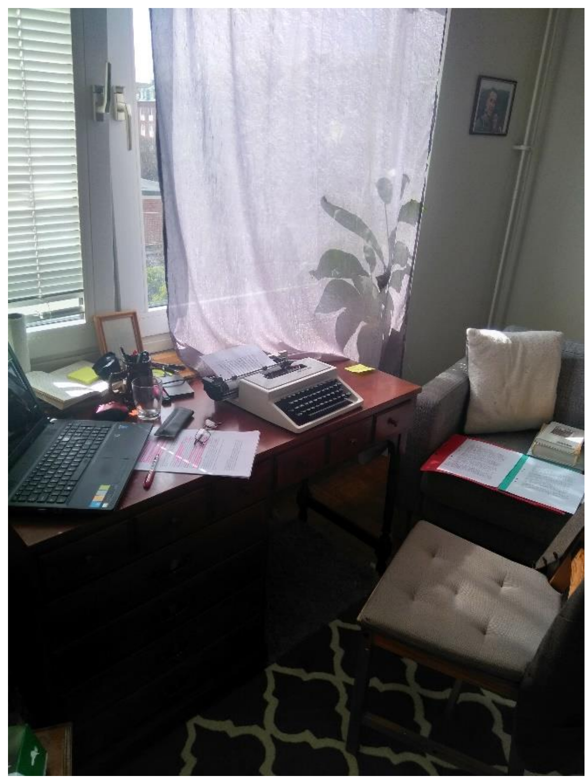

Fig. 7. The sound of a typewriter is rarely heard these days but it's not forgotten. Photo: Tim Elfström.

It's easy, with the help of computers, to transform organic human beings to engineering units. To these units we can assign quantified properties such as "threshold of hearing", "specific gravity" or "yearly income" and then create programs to predict behaviours or tendencies. What happens if we miss some essential parameter? My favourite example of this is BIM – Building Information Modelling. I'm not arguing against the use of BIM but I wish to point out the danger of it. Might we not easily ignore all those details that are not included in the catalogue of objects? How do we characterize sound in a BIM model? We can't see sound, so we need some other tool to "visualize" it. I fear that, in some cases, what can't be seen isn't considered to exist.

By including this little chapter, I hope to make it quite clear that sound matters to people. It shapes the world around us, we have an idea of the "mood" of a place even before we see it. Our experiences cause us to have expectations of certain sounds to be connected to certain visual impressions. The sound of cars tells us that there is a road nearby. The sound of hammering tells us that someone is building or making something. We often hear things before we see them and seeing things without hearing them first can make us very surprised. We expect a gothic cathedral to have a lot of reverberation and if we don't hear it we will be confused. Although, a cathedral might be more useful with a more moderate reverberation as it might then be used for a more varied range of events; unless one of the key functions is to house organ recitals that have been written for rooms with a long reverberation time/echo.

Mrs. Dalloway by Virginia Woolf

> "What a lark! What a plunge! For so it had always seemed to her when, with a little squeak of the hinges, which she could hear now, she had burst open the French windows and plunged at Bourton into the open air."

These lines can be found on the very first page of Virginia Woolf's classic from 1925. The lark, I think, is to be considered heard rather than seen. The plunge is reminiscent of the sensation one gets when jumping into less-than-warm water. By evoking physical and

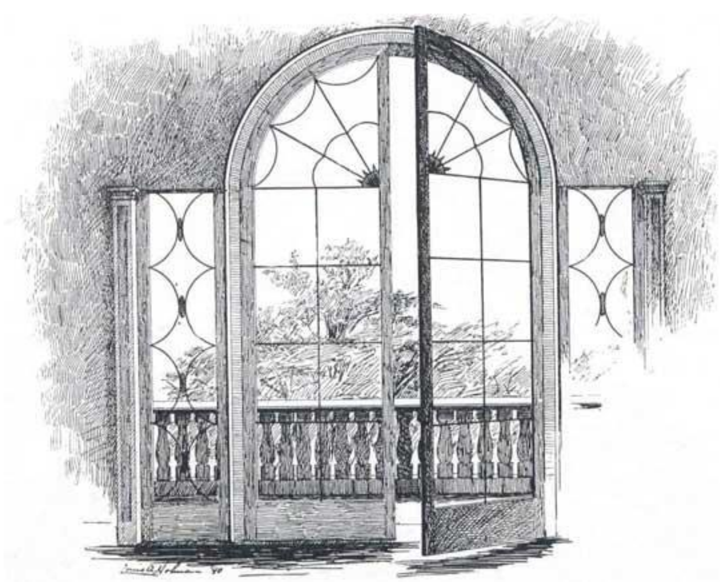

Fig. 8. Drawing of French windows, Victorian or so. Image: www.thedowneastdilettante.blogspot.com

auditory sensations, Woolf brings the reader directly onto the scene. It's the difference between watching Mrs. Dalloway bursting through the French windows, and joining her. Anyone who has stuck their nose out into fresh morning air will remember the sensation. Describing the visual quality of morning air simply isn't enough.

Lady Chatterley's lover by D.H. Lawrence

> "Connie was accustomed to Kensington or the Scotch hills or the Sussex downs: that was her England. With the stoicism of the young she took in the utter, soulless ugliness of the coal-and-iron Midlands at a glance, and left it at what it was: unbelievable and not to be thought about. From the rather dismal rooms at Wragby she heard the rattle-rattle of the screens at the pit, the puff of the winding-engine, the clink-clink of shunting trucks, and the hoarse little whistle of the colliery locomotives."

Lawrence then continues by recalling the stench of the

> "sulphurous combustion of the earth's excrement."

in his description of the depressive state of the English Midlands in the 1920's; coalmines everywhere. Lawrence uses this setting to tell the story of two fragile people's struggle to survive in a hard world.

When "Lady Chatterley's Lover" was first published it was considered highly scandalous because it celebrated physical intimacy between people. Many forget, though, that one of its main objectives was to criticize the inhumanity of industrialization. Lawrence brings to literary life the sounds and smells of a world that is ill fitted for human habitation. It's

> "the world of the mechanical greedy, greedy mechanism and mechanised greed",

where noses are insulted by toxic fumes, ears are assaulted and damaged by the sounds of primitive industry and the softness of the grass is marred by the presence of grey ashes and dust. The text may be a century old but people are the same. I might comment that todays' world seems to be more about digitalized greed than mechanized greed but the governing principle hasn't changed. Today our ears are assaulted by commercial messages, background music, traffic noise and the pings and rings of a thousand cell-phones walking around with their owners.

Basic room acoustics theory

This section gives a brief introduction to some basic phenomena in room acoustics. I have tried to simplify the text as much as I can without losing too much precision. Acoustics on this level is not so much about mathematics as about a conceptual understanding of how soundwaves move and interact in rooms and what that has to do with people and the architectural experience.

Soundwaves and the concept of frequency

To understand the behaviour of sound in rooms, we need to have some grasp of a few basic concepts from the world of physics. Sound moves in air, which consists of molecules. The number of molecules per volume will determine the air pressure. If we "rope off" a small volume in the room and "count" the number of particles there and then do the same for an adjacent volume, we would probably get slightly different results from the two, even if they are exactly the same size. The particles in the more crowded volume would be trying to get to the less crowded part of the room, because nature strives towards balance. The two volumes are said to have different air pressure. When particles move from one place to another, we feel an air flow – a very weak wind. If a room is in balance, with the air particles evenly spread, and something gives the particles in one part of the room a slight push, they will push on their comrades, who push on their comrades, who push on their comrades, a little weaker for each time. This is a pressure wave; in air it will be a soundwave. Particles made to push on each other and our ears are designed to perceive these minute variations in pressure – particles moving in and out of the ear drum, causing the ears' membranes to move with them. We hear.

What we hear is variations in the pressure of the air in the ear, which is connected to the air outside the ear. These changes can be slow or fast, depending on what's caused the pressure to variate at all. The rapidity of the change from high to low pressure and back again is called frequency. Frequency is a term used in many branches of physics and describes how fast something changes from something to something else and back again. Frequency in acoustics means how many of these cycles the air pressure does per second. During one cycle, the pressure goes from zero to maximum, down to minimum and then back to zero. Then the next cycle starts. A sound of 1000 Hz (Hertz) does one thousand cycles per second. The frequency is 1000 Hz. The higher the frequency, the brighter the sound. The human ear has the capacity to hear sounds from 20 Hz to 20000 Hz – a great span!

The tone that can be heard in a telephone receiver is an example of a sound that has one single frequency, often 440 Hz. A tuning fork is another example. Most sounds, however, consist of a multitude of different sounds. That's why we can hear if a musical note is played on a guitar or on a piano even if the fundamental note is the same. Rooms also respond differently to different frequencies. A room can often have a much longer reverberation time at low frequencies than at high.

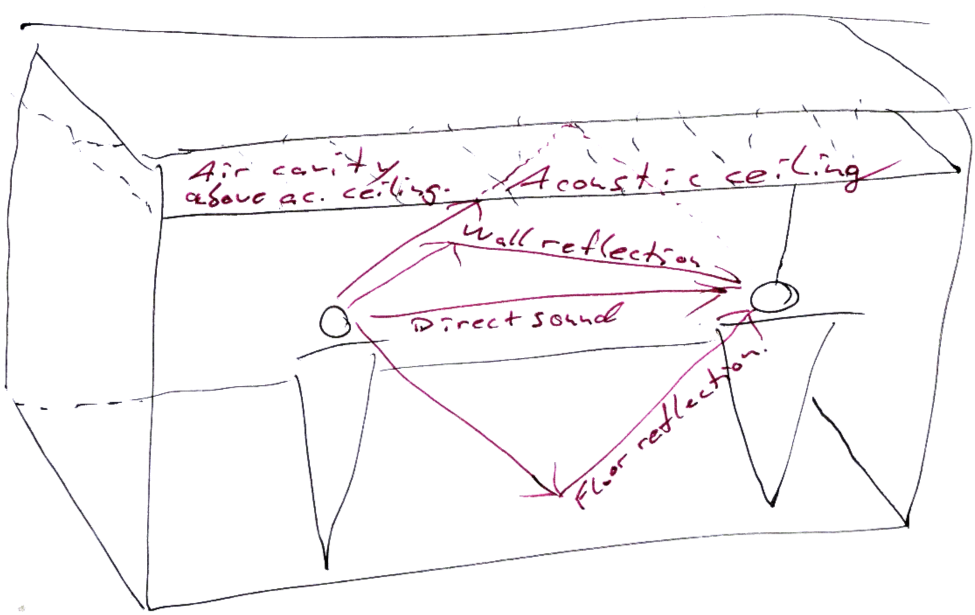

Fig. 9. Different ways for sound to travel from speaker to listener. They're all relevant.

Direct sound and its reflections

Two persons facing each other could easily have a satisfactory conversation utilizing only the sound that travels directly from the speakers' mouth to the listeners' ear. This means that the sound reaches the ear only once and that the listener must be alert and ready if he or she is not to miss anything. A reflection, on the other hand, is a "package" of sound energy that has travelled from the speaker in some other direction than the intended and that has "bounced" back from some surface. It therefore reaches the listener some milliseconds later than the direct sound. In a room, there are normally many reflections and some "packages" can pass by several times as they bounce around the room. See Fig. 9. So,

Perceived sound = Direct Sound + Reflections.

Given that the speaker and listener remain static; the direct sound will not change. If the space around them changes, however, the reflections will be different and therefore the quality of the conversation.

"Balanced" vs. "unbalanced" rooms

Balance is a word that I like to use to explain the concept of "diffuseness". In room acoustics, diffuseness is used to describe the evenness of the sound field – how evenly spread the reflections are in the volume of the room. A diffuse sound field is one where the sound bounces in every direction quite equally and independently of whether it's going upwards or sideways. The sound energy is evenly spread throughout the room.

An unbalanced room is a room where it matters to a soundwave in which direction it's going and which surface it hits. A common example is a room with a sound-absorbing ceiling and flat, hard walls. A soundwave that goes off upwards will be absorbed by the ceiling instead of bouncing back down. Soundwaves that travel horizontally, on the other hand, will have nothing to prevent them from bouncing between the walls far longer than the soundwaves that travelled up into the ceiling. This scenario is strictly non-diffuse – uneven, "unbalanced".

What if a room had absorbing materials on all surfaces? Well, then the perceived sound would be only the direct sound and therefore depend greatly on which way the sound source was facing. This is a non-diffuse scenario, since the sound energy will not be evenly distributed in the room.

Since most rooms are non-diffuse, it's important to consider how the sound energy will spread in the room. By making reflecting objects "point" towards absorbers, more sound energy can be absorbed than if the absorbers had been left alone. Absorbers don't attract sound; they only absorb what comes their way.

Measuring sound

The field of room acoustics has a very large number of different parameters that can be measured in order to describe acoustic performance in a quantitative (engineering-like) way.

In architecture other than auditoria and such, only a few of these parameters are necessary. What I will explain here is a concept called "Room Acoustic Comfort" that was developed by Saint-Gobain Ecophon AB. It's a set of three descriptors that have been found to give a good overview of the acoustic performance of an "ordinary room" such as a conference room, a classroom or a hospital ward. The parameters are defined in the standard ISO 3382-1 and I shall try to explain what they mean and what they have to do with architecture.

In most cases, acoustics are measured by creating a sound impulse and measuring the rooms response to that sound. In former days, the principal method was to create a loud bang (pistol shot, drop something heavy, bang two things together) and listen to how fast the sound disappeared again. The "bang" would typically be followed by an echo – called "reverberation" in room acoustics - and the length of this is called the "reverberation time". How this works in detail is explained later in this chapter. The reverberation time is measured in seconds.

While reverberation is measured in time, sound level is measured in decibels, written dB. It is a measure of the amount of sound energy – the thing you increase when turning up the volume on a stereo. Decibels is a logarithmic scale, which has as a consequence that a small change in numbers means a great difference in perceived sound level. An increase in sound level of 3 dB means that the amount of sound energy has been doubled. 0 dB is the lowest sound level that can be heard by human ears, though many animals can hear even weaker sounds. The mathematics behind this seemingly strange system are outside the scope of this text, however elegant and interesting they may be. Now that we've seen the concept of sound level and introduced the decibel scale, we can have another quick look at the reverberation concept. The room-acoustic parameter Reverberation time (T60, T30 or T20) is the time it takes for the sound level in a room to drop 60 dB. That is an enormous change in sound level! That's why it's called T60. T30 and T20 are the same thing, only measured in slightly different ways.

Another parameter is Speech Clarity, which is more or less what it sounds like: a parameter that indicates how well speech can be heard in a room. Speech Clarity is a bit trickier than Reverberation Time but at least as useful. We discussed earlier how perceived sound consists of direct sound and its reflections and Clarity has to do with the time it takes for the reflections to reach the listener after the direct sound has been created. Reflections that reach the listener very soon after the direct sound enhance speech clarity but reflections that arrive late can lessen it. For speech, the limit for early reflections is set to 50 ms after the direct sound. For this reason, Speech Clarity is shortened C_{50}. Speech Clarity is defined as the ratio between the sound energy in the first 50 ms and everything that arrives later than 50 ms after the direct sound. It's given in decibels.

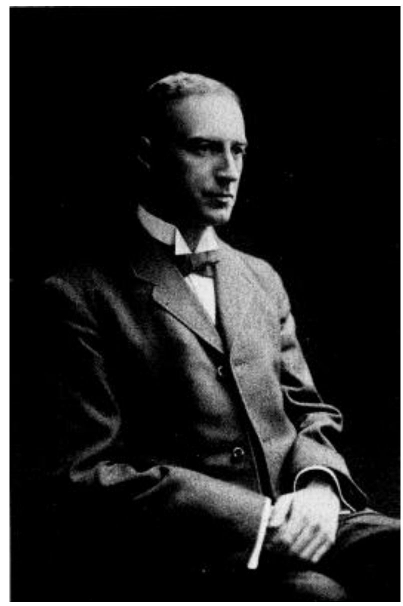
Fig. 10. Wallace Clement Sabine, Harvard University.

Speech Clarity and Reverberation Time are related to each other and often strongly correlated. However, it's perfectly possible to have a decent Reverberation Time but rather poor Speech Clarity. The reason for this is that reverberation has a lot to do with the size of the room while Clarity is more dependent on the reflection paths that the sound takes from the source to the receiver (speaker to listener, for example). This is true both with a lot of sound in the room and with very little.

The classical way of describing acoustic performance is to measure the reverberation time and nothing else. This "system" was developed for large lecture halls, concert halls and theatres. Reverberation Time was (and is still) calculated using Sabine's formula, which was developed by a physicist called W.C. Sabine in the late 19th century. Things have evolved since then but Sabine's formula is still used widely, if not always with accurate results.

The standard ISO-3382 defines room acoustic parameters & measurement techniques. It's important to have a standard since there are many ways of describing acoustic phenomena. What really happens is that soundwaves propagate through the air but that is far too complicated to be calculated in a mathematically exact manner. Simplifications have to be used and the standard is an agreement about how we should simplify things so that we all do it in the same way.

A typical standard-defined parameter is called "Strength", denoted "G", and is a way of describing how well the room can dispose of sound energy. Strength is measured by sending a constant sound of known level into the room and measuring the sound level at a few different points in the room. The sound level will be constant over time since the sound is sent out continuously. If the room has a lot of absorptive material in it, Strength will be lower than if the room has only hard surfaces. What happens is that a room with a lot of absorptive material in it will be able to dispose of more sound energy and therefore reach an equilibrium between "added" and "removed" at a lower point than if there is less absorptive material. The parameter Strength thus depends only on the rooms volume and the amount of absorptive material. It's possible to manipulate Reverberation time and Clarity without affecting Strength. Strength is measured in decibels but is not the same as Sound Level, since Strength is the rooms response to a known sound while Sound Level is the amount of sound energy in the room regardless of where the sound is coming from.

More about Reverberation Time

This really is the grandmother of all acoustic measurements. It was invented by the American physicist Wallace Clement Sabine (1868-1919) in the late 1890's, as part of his work on improving the acoustics of a lecture theatre. Sabine discovered that there is a clear relationship between the rooms size, the amount of absorptive material present and the time it takes for a sound impulse to stop reverberating. The time it takes for a sound to drop in level by 60 dB (decibels) is called the reverberation time and can be calculated using Sabine's formula:

$$T_{60} = 0{,}161 \times \left(\frac{V}{A}\right) (s)$$

Where V is the room volume (m^3) and A is the equivalent absorption area measured in the unit "sabin" or in this case "m^2sabin", to make it clear that SI units are being used. "m^2sabin" isn't a unit that describes an actual physical surface. It is a sum of all absorptive surfaces in the room recalculated to correspond to the size they would have if they yielded 100% absorption. Example: A surface of 2 m^2 that absorbs 50% of the sound that hits it is written as 1 m^2sabin. 50% absorption is written as an "absorption coefficient" of 0,5. Thus:

$$A = S \times \propto \ (m^2 sabin)$$

Where S is the actual surface area and a is the absorption coefficient. The "A" used in Sabine's formula is the sum of all absorptive surfaces in the room and their respective absorption coefficients. 1 m^2sabin = 1 m^2 hole in the wall where sound is let out into "nothingness". This is a simplification but is true enough to serve as an illuminating example. If only half of the sound was let out through the hole, it would need to be twice as big to have the same effect as if all the sound was let out.

The "Grazing Field"

Sabine's formula has some limitations. It assumes that the room has a diffuse sound field, where the amount of sound energy is the same in every point in the room and reflections go in all directions (up, down, to the side and everything in between). In rooms that have little or no absorption and where no dimension (length, width or height) is much larger or smaller than the others, this is tolerably true. The lecture theatres in which Sabine developed his formula would have been such spaces, just like most rooms were at that time in history. Problems arise when a lot of absorption is allocated to one part of the room (usually the ceiling). Then the sound field is no longer even, since the sound that hits the ceiling is absorbed but the sound that "rotates" between the walls stays in the room much longer. Rooms like this could therefore be said to have two

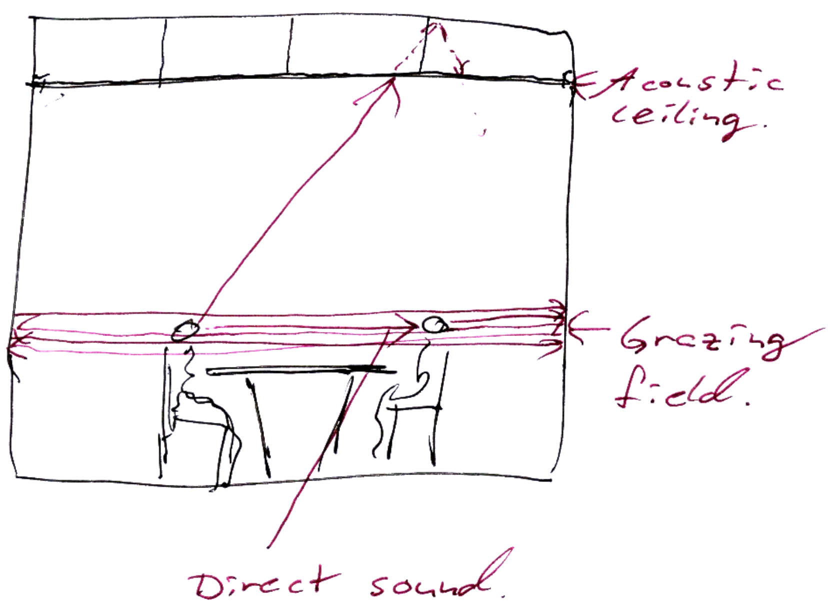

Fig. 11. A room with two hard walls facing each other. The ceiling has no effect on the grazing field.

reverberation times: one vertical and one horizontal. The field that reverberates between the walls is called a "grazing field" and causes Sabine's formula to overestimate the effect of the absorption in the ceiling.

Another problem with Sabine's formula is that it uses only a single absorption coefficient. In reality, absorption is greatly dependent on the angle from which a soundwave hits the absorptive surface and the frequency of the sound in question. If the angle of incidence is perpendicular to the surface, the absorption is much higher than if it's nearly parallel. The absorption coefficient used in Sabine's formula is typically one that has been calculated by averaging absorption coefficients measured with different angles of incidence. This may be good enough for some materials but causes problems for others.

On the whole, Sabine's formula is useful but its limitations shouldn't be forgotten. Using it as a prediction tool for rooms with acoustic ceilings is inadvisable unless the grazing field can be disbanded or absorbed away.

For classrooms and office spaces, a common recommendation is to have a reverberation time of 0,6 seconds. If the reverberation time climbs much over 1 second it will be perceived as an annoyingly echoing room. For music, on the other hand, a reverberation time of 1-2,5 seconds can be used depending on the size of the room and the type of music that is to be played. If the reverberation time is too short the room will be too "dry" or "dead" for the music to be fully appreciated. This is why out-door concerts generally sound much weaker than they would have done in-doors. In a free field, the reverberation time is 0.

Speech Clarity - Early/late reflections

"Speech Clarity" is the name of this parameter because it tries to give an indication of how clearly speech can be heard in a room. If Speech Clarity is high, the speech can be heard "clear as crystal" and if it's low the speech is perceived as "blurry" and indistinct. An example of extremely good speech clarity can be found in a middle-aged coniferous forest, where the stems are just the right diameter to reflect the high frequencies that contain speech information while letting low frequencies disappear into the distance. Speech can be defined as two different types of sound: vowels and consonants. Vowels are low in frequency (500-1000 Hz, sometimes lower) and don't carry a lot of information. Consonants are higher in frequency (1000-4000 Hz) and are absolutely necessary if the speech is to be intelligible. Consider abbreviations: a consonant is rarely omitted but vowels are ignored liberally. If speech is to be heard clearly, the consonants should be supported and spoken words shouldn't linger in the air and blur the words that come after. I like to compare this to solos in jazz music – notes shouldn't linger too long because there are more coming in a rapid stream and each needs to be heard as a distinct link in the chain.

Fig. 12. A classroom set in a spruce forest. Photo: www.ljudskolan.se.

More about Speech Clarity – C_{50}

Speech Clarity is defined as the ratio between the sound energy that arrives to the listener/receiver within the first 50 milliseconds and everything that arrives later. The formula is given below (for the particularly interested reader):

Speech Clarity:

$$C_{50} = 10 \times \log\left(\frac{\int_0^{50} P^2(t)dt}{\int_{50}^{\infty} P^2(t)dt}\right) (dB)$$

Where p is the sound pressure (in Pascals). 50 ms has been determined to be a good limit for early reflections where speech is concerned. If music is the intended sound, 80 ms is used and the parameter is called C_{80}. Since C_{50} is given in dB, a small change in absolute numbers can make a significant change in how the room is perceived. A change of 3 dB corresponds to a doubling of the sound energy. A good classroom will likely have a C_{50} of 6-8 dB. A lower value will cause the students to hear the teacher less clearly, which leads to fatigue and poorer learning results.

In the worst cases, the back wall of a long room causes a very late reflection to come back to the speaker long after all other reflections have disappeared. This is disturbing to everyone involved and should be avoided. As a rule, reflections from the side walls and ceiling can be useful but the back walls reflections are detrimental to Speech Clarity.

More about Strength, G

Strength is different from Reverberation time and Speech Clarity since it's not affected by the way sound is reflected in the room or where absorption is allocated. Strength is the sound pressure level (in dB) at which a constant sound source sends out as much energy as the room absorbs. This is called "Steady State" and is created with a calibrated sound source (much like a fan) that sends out a noise of known and constant sound energy. Since the sound is continuously added to the room, there won't be a change in sound level once the equilibrium has been reached. If the sound pressure level is measured now (in several positions in the room) and the effect of the sound source is known, Strength can be calculated as follows:

$$G = L_{P.RECEIVER} - L_{W.SOURCE} + 31 \text{ (dB)}$$

L_P is a measured sound pressure level and L_W is the effect level, which isn't affected by anything other than the power of the source. Thus, the source will give the same L_W in any space but the size and properties of the room will cause L_P to vary greatly. For a given room, Strength can really only be changed by adding or removing absorptive material or changing the dimensions of the room.

Steady State vs "Sound Decay"

Fig. 13 shows two types of sound fields. To the left, a constant sound source is active and causing the sound to be reflected off every surface all the time and disappear when absorbed. The added energy is at equilibrium with the absorbed energy. The room to the right has had a sound impulse which is now decaying. The yellow waves belong to the diffuse sound field that works in every direction. The white waves belong to the grazing field that reverberates between the walls only. The left case is used to measure Strength but Reverberation time and Speech Clarity will be a combination of the two. The ratio between white arrows and yellow arrows is important as it determines the diffuseness of the sound field. Both of these indicators are needed to get a good description of the room. Reverberation time and Speech Clarity give information about the reflection paths and the distribution between early and late reflections. Strength gives a value of the over-all sound level in the room. If the room dimensions are known, the amount of absorption can be estimated from Strength.

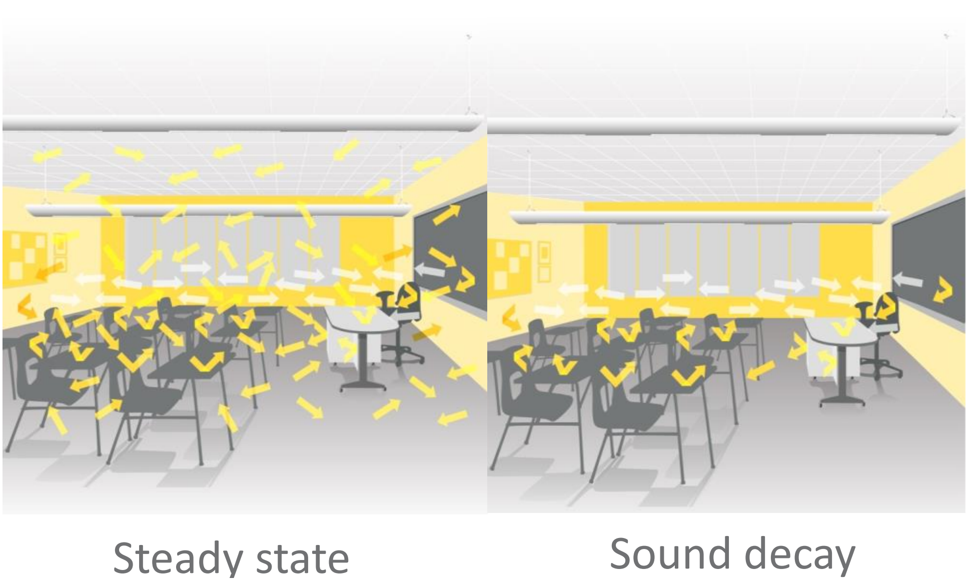

Fig. 13. Sound fields in rooms. White arrows: Grazing waves. Yellow arrows: Diffuse waves. Picture: S-G Ecophon AB.

Wavelength

Wavelength is another central concept from the world of physics. While frequency describes how fast each cycle of change is, wavelength is the physical distance that the soundwave travels during one cycle. Higher frequency means shorter wavelength. The lowest audible sound (to humans) is 20 Hz, which corresponds to a wavelength of around 17 m. 20 kHz, the highest audible frequency, has a wavelength of around 17 mm.

Wavelength can be calculated as:

$$\lambda = \frac{c}{f}\ (m)$$

Where

λ = wavelength in metres

c = speed of sound in air in m/s

f = Frequency in Hertz (Hz)

The speed of sound in air is usually taken to be 341 m/s, which means that

$$\lambda = \frac{341}{f}\ (\mathrm{m})$$

At 100 Hz, the wavelength is therefore

$$\lambda = \frac{341}{100} \approx 3{,}4\ \mathrm{m}$$

The lowest frequency that is audible to humans is 20 Hz, which corresponds to a wavelength:

$$\lambda = \frac{341}{20} \approx 17\ \mathrm{m}$$

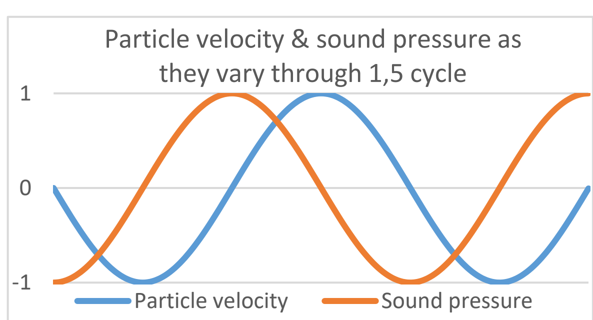

Fig. 14. The particle velocity will always be zero as the wave hits a wall, where the sound pressure is max. The total energy, sound pressure and particle velocity, will always be the same in a harmonic oscillation.

Acoustic absorbers

The most common way of modifying the acoustic behaviour of a room is to add (or remove) absorbers. Absorbers are materials that convert sound energy to heat as it passes through them. The most common ones are acoustic ceilings made of mineral wool or wood-cement mixtures, textiles such as thick curtains and furniture like sofas or armchairs.

The general idea is to convert sound energy to heat as it passes through the absorber. This can be accomplished in several ways but the basis of most arrangements is the porous absorber. If a material has a high porosity and is open to air flowing through it, the friction created between the air and the pore walls and within the air itself will cause the sound energy to be dissipated as heat. In materials like glass wool this works extremely well. The problem is that absorbers only work where particle velocity is high, which means that the air is moving around a lot. This happens where the waves kinetic energy is at its peak and not where the pressure is the highest (see Fig. 14). The pressure is always highest at a boundary surface (a wall, for instance) and thus the particle velocity by the same surface is zero, which means that no absorption can take place right by a wall. The particle velocity is the highest ¼ of the wavelength away from the wall. For high frequencies, this might be a few centimetres only but for low frequencies it can be 0,5-1 meter or several times more. To absorb low-frequency energy in an effective way, a porous absorber must be placed 0,5-1 meter or more from the wall. This is rarely practical, so for low frequencies a slightly different strategy has to be used.

Low-frequency absorption

The typical way of creating low-frequency absorption is to "collect" low-frequency energy in a resonating chamber and absorb the energy as it enters and leaves the chamber through small holes. The principle is simple: a chamber with a certain volume has holes in it that allow air (sound waves) to travel into the chamber. The chamber is such a size and shape that waves of certain frequencies can easily resonate inside it. This creates a powerful movement of air through the holes connecting the chamber with the outside. If an absorbing material is placed inside the chamber and in the holes (the "necks"), the energy can be absorbed where it is the most concentrated. Arrangements that use this principle are called "resonant absorbers" or "Helmholtz absorbers" and they come in many shapes and sizes. Two examples are flat, wall-mounted "slot absorbers" and corner- or ceiling-mounted deeper Helmholtz-resonators.

The concentration of energy is always greatest in corners and therefore absorption can also be placed there with good results. However, corners can also be sensitive architecturally and so a flat but wider slot absorber could in many cases be a more practical choice. The resonant absorber is also a narrow-band arrangement, which means that it is only effective in a limited frequency range, which is defined by the different geometrical properties of the resonator. The slot absorber is typically broader in its spectrum but at the same time less effective, even at its best, than the single-cavity version is at its optimum frequency. An absorbing ceiling could also be said to be a form of resonator, since it creates a closed air chamber above it. The distance between the ceiling and the soffit is of great importance if the ceiling is to perform well at low frequencies (which it can do). The problem of absorbing low frequencies with only porous absorbers is primarily found when the absorbers are mounted on walls, where a very flat construction is necessary. For further reading, see Trevor Cox & Peter D'Antonio's book "Acoustic Absorbers and Diffusers"[3].

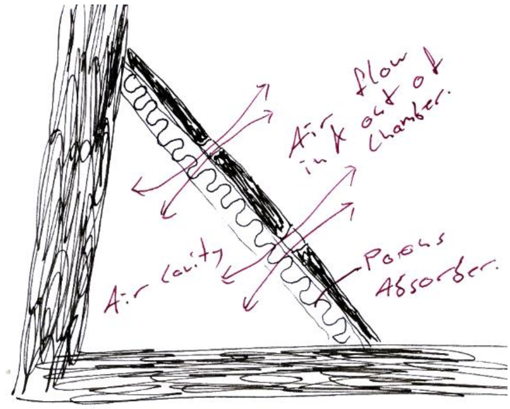

Fig. 15. Helmholtz resonator/absorber conctructed in a corner. This arrangement typically runs the whole height of the room. Plan drawing not in scale.

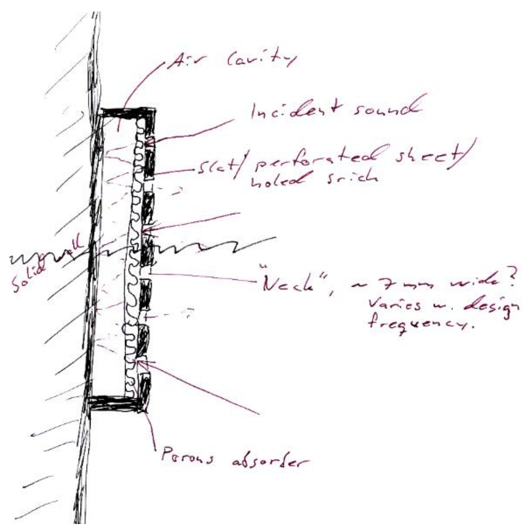

Fig. 16. A sketch of a slat absorber. Not in scale but showing the openings in the cover and the porous absorber behind. All measurements will vary with the acoustic requirements.

[3] (Cox & D'Antonio, 2004)

Scattering & Diffusion

If the idea of sound being waves is abandoned for a moment and the idea of sound as rays is taken up instead, the following statement can be considered: Sound will be reflected off surfaces in the same way as light. The angle at which it hits the surface will determine the angle at which is leaves the surface. This is called "specular reflection" and is true about sound under certain conditions.

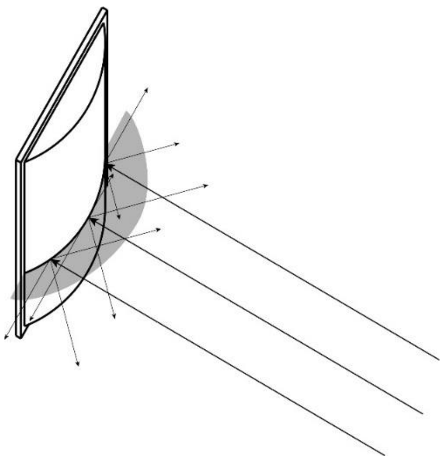

Fig. 17. A good diffuser will spread sound evenly

The difference between sound and light is first and foremost the wavelengths. Light is waves with extremely short wavelengths. Sound, on the other hand, has wavelengths that can easily be measured in metres. In fact, lower frequencies of sound give wavelengths of several metres.

Since the particle movement is greatest at ¼ of the wavelength from a boundary surface, the chance of influencing the wave is also greatest at this point. Sound waves have the power to "sneak" around objects that are much smaller than their own wavelength (perhaps 1/10 of the wave length or smaller). Objects that are ¼ of the wavelength or larger in size can completely alter the wave's direction and/or split it up into many weaker waves that head off in different directions. This is called diffusion (or scattering) and is essential to the acoustic design of rooms. If flat surfaces are used, the sound will be reflected from them in much the same way as light off a mirror. If geometrical objects of significant size are present in the room, these specular reflections will be broken up into many smaller reflections that make the rooms sound field more even: the diffuseness increases and the sound field appears more balanced. Furniture is an excellent example of this. Sofas and beds typically absorb a lot of energy and hard objects like chairs, tables and book shelves scatter energy and diffuse the sound field. The bookshelves are particularly useful here since its differently sized

Fig. 18. RPG Modffusor. This is a typical diffuser that spreads sound horizontally. If it's turned 90 degrees it will spread sound vertically instead. The dimensions of the cavities are mathematically determined. Photo: www.rpgeurope.com

cavities (variously sized books and occasional holes where there are no books) will correspond to fractions of different wale lengths and thus scatter many different frequencies. If a bookshelf has a hole in it with the depth 0,3 m, the following can be said:

$$\lambda = 0{,}3 \times 4 = 1{,}2\ m$$

$$f = \frac{341}{1{,}2} \approx 285\ Hz$$

Thus, this hole will very effectively scatter waves with the frequency 285 Hz and everything close to it. It's likely to have some effect even down towards 200 Hz, though it will be smaller. These are low frequencies that can easily cause problems with speech clarity and scattering them (so that at least a part of the energy goes off into the ceiling) is desirable.

Scattering and diffusion are two expressions that are often mixed up. They refer to the same phenomenon but from different perspectives. Diffusion has to do with the evenness of the energy that is reflected from an object – if the sound is spread out in many different directions or if it all goes the same way. Scattering is a term mainly used in simulation software and will not be further discussed here.

Fig. 17 & Fig. 18 show how diffusers can be designed to spread sound in a given plane. As long as the edges are exposed, the diffuser will spread sound the other way as well but much less evenly. Fig. 19 shows two polar diagrams that compare the

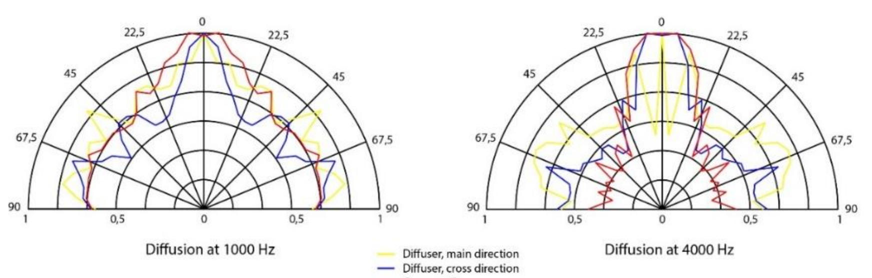

Fig. 19. The diffusion of each object at 1000 Hz & 4000 Hz respectively. They are similar at 1000 Hz but quite different at 4000 Hz.

diffusion of three different objects at two different frequencies. The sound comes in perpendicularly from the object and is spread around its circumference according to the lines. The further the line is from the centre at a point, the stronger the reflection in that direction. As can be seen, the diffusion varies between the frequencies, more for some objects than for others. A nearly circular curve means good and even diffusion while a "pointy" curve means poorer diffusion. The objects measured for the graphs in Fig. 19 were ca $600\ x\ 600\ mm$ but had different curvatures.

Changing acoustic performance

When a room has poor acoustic properties there are often several ways of improving it. For ordinary rooms, the most common way is to add absorption – a ceiling and some wall panels. The ceiling lowers the general sound level in the room (Strength) and the wall panels remove or weaken the grazing field. The ceiling is needed in these spaces and there is often no real alternative. The wall panels on the other hand, aren't the only way of breaking up the grazing field. That might be done very well with diffusers that redirect the energy, either to remove it by sending it into the ceiling or to disband disturbing echoes by breaking up unified wave fronts into many smaller "sound packages". The main difference between wall-mounted absorbers and diffusers is that absorbers actually remove sound energy while diffusers only redirect it. The choice of one over the other will partly depend on if the energy is desired or not.

Just Noticeable Difference

Shortened JND, this is a series of values that have been established to indicate how great a change needs to be for the human ear to perceive it. It's a rather crude estimation but gives some idea of the resolution of the measurements used in room acoustics. JND for Reverberation time is 5% and for Speech Clarity and Strength it's $1\ dB$. The error of measurement is generally smaller than this and therefore JND can be referred to when the significance of a result is discussed.

Theory applied in a case study

While acoustics should ideally be included in the original design, retrofits are extremely common. This chapter uses a restaurant as a case study to discuss different ways of applying the techniques described in the previous chapter. The restaurant in question isn't by no means an acoustic disaster but has some common traits that aren't necessarily desirable.

Skissernas museum, Lund

This is a new restaurant. It's located in the addition to Skissernas Museum in Lund and was designed by Elding Oscarsson and awarded with the Kasper Salin Prize in 2017. It's a visually pleasing and very elegant piece of architecture. One of its problems is that it has a reputation for being quite noisy and shrill, in contrast with the otherwise cosy atmosphere. As the number of visitors passes a handful, the noise level rises beyond what is acceptable in a space adapted for human conversation. The walls consist of birch plywood and large windows which allows a strong grazing field to spring up.

Some measurements were made, to get a solid point from which to start. While not surprising, the results clearly show that the space lacks balance between the high and the low frequencies, making the space unable to live up to its full potential as a popular and high-end place to meet and eat.

Fig. 20. Skissernas Museum, Lund. Architect: Elding Oscarsson. Photo: Tim Elfström

Measurement results

Fig. 21 shows the measurement results.

The topmost graph shows the **reverberation time** which, curiously enough, is lower at low frequencies. This is unusual and indicates a strong grazing field. It also makes the room feel quite hard, since the low frequencies tend to soften the sound environment. It's also a problem since speech is the primary sound source and typically found at 1000-4000 Hz, where the reverberation time is longer.

Speech Clarity is poor in a more traditional manner – worst at low frequencies. A common recommendation is to have a C_{50} of 0,6-0,8 dB in classrooms. In this restaurant, 50-60 guests can be dining at the same time and produce a lot of sound energy. This calls for a higher C_{50} if each company is to be able to converse.

Strength is more difficult to put in context, since it's less well referenced for different types of rooms. The higher value at low frequencies is consistent with the poor Clarity and indicates that the absorption works less well below 500 Hz.

The room is almost exactly 100 m^2 and 3,5 m high, which gives a total volume of 350 m^3.

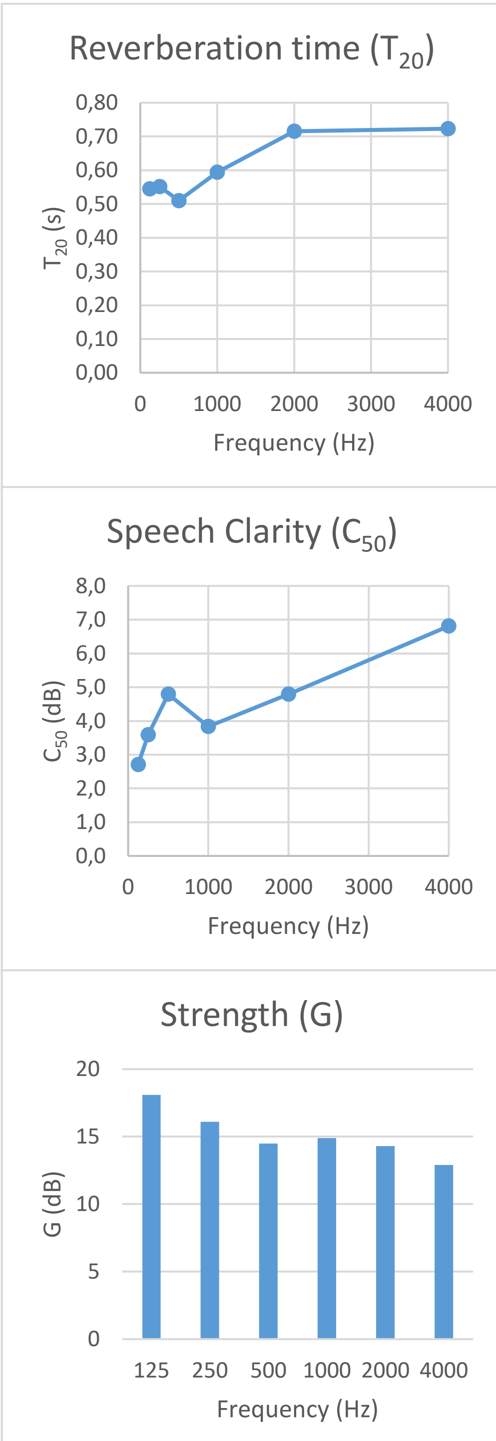

Fig. 21. Measurements in the restaurant at Skissernas Museum, Lund.

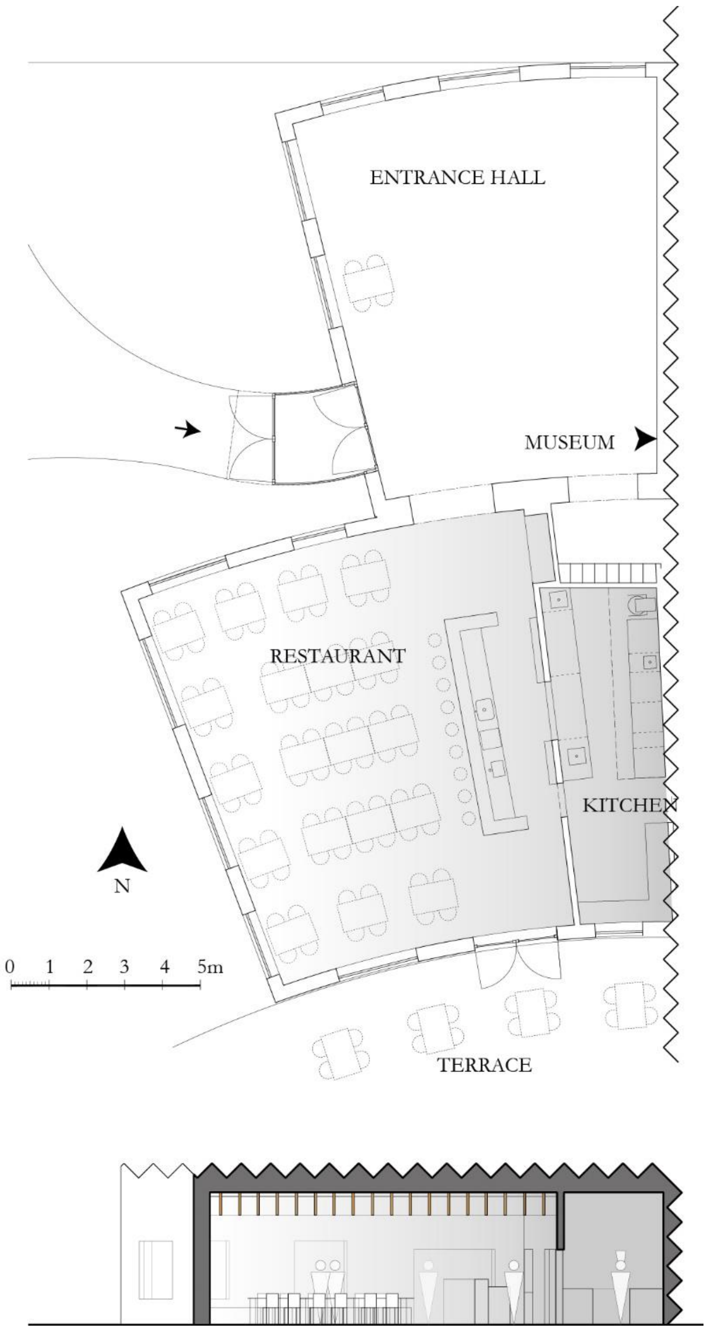

Fig. 22. Plan & Section of the restaurant.

Room surfaces

The room consists of four major surface types:

- Birch plywood walls
- Glass windows
- Wood-cement acoustic ceiling
- Concrete floor

The building proprietor informs me that the acoustic ceiling is fitted on wooden slats, 80-100 mm from the soffit. This gives some extra low-frequency absorption than if the ceiling had been fitted directly onto the soffit. As can be seen in Fig. 21, the reverberation time is lower at low frequencies than at high, which indicates that the long, difficult waves aren't problematic. The opening between the restaurant and the foyer is also likely to have some effect here, by letting the sound pass out into the larger foyer instead of reverberating inside the restaurant. If the low-frequency reverberation needed to be lowered, increasing the air gap above the acoustic ceiling to ca 200 mm might have been a good first step.

The plywood and the glass constituting the walls are more or less equally absorptive, which in this case means that they reflect almost all the soundwaves that hit them. This means that a grazing field can exist quite freely, only disturbed by the furniture which in this case isn't very effective. For the purposes of this discussion, the concrete floor doesn't absorb any sound either.

Fig. 23. Walls and ceiling are hard, flat surfaces. Birch plywood and glass. Photo: Tim Elfström.

In most texts about room acoustics, the "exact" absorption coefficients of the different materials would now be listed. In this case it will suffice to say that all except the acoustic ceiling have very low absorption coefficients. Glass and concrete are close to zero. The walls may offer some low-frequency absorption if there's a cavity behind them but in the higher frequencies they reflect almost everything as well.

In terms of acoustics, furniture can have two functions: absorbing sound and diffusing/scattering sound. Absorption requires stuffing but all furniture diffuses sound. At Skissernas, the chairs will only

The ceiling is hung underneath an 80-100 mm air gap, according to the buildings proprietor.

Fig. 24. Wood-cement acoustic ceiling.

diffuse since they have no stuffing. The sofas along the sides may have some little effect but compared to the size of the room the small amount of stuffing is likely to have only a marginal effect. Most of the absorption below the ceiling will be the guests themselves.

Diagnosis

Fig. 25 shows the principle problem of this restaurant. With the wall surfaces hard and flat, the sound is allowed to reverberate between the walls and remain annoyingly long before fading. To solve this problem, the walls need to break up, redirect or absorb this sound. The two most obvious solutions are to fit absorbing panels directly onto the walls (where possible) and/or to fit diffusers that redirect the sound upwards, into the acoustic ceiling which is already fitted. As we could see in Fig. 21, Reverberation time is poor in the high frequencies but adequate in the lower part of the spectrum. This is also why the room feels quite hard and cold, rather than soft and cosy. Cosiness, in this case, would require a different balance between high and low frequencies, and not too much reverberation in any frequency.

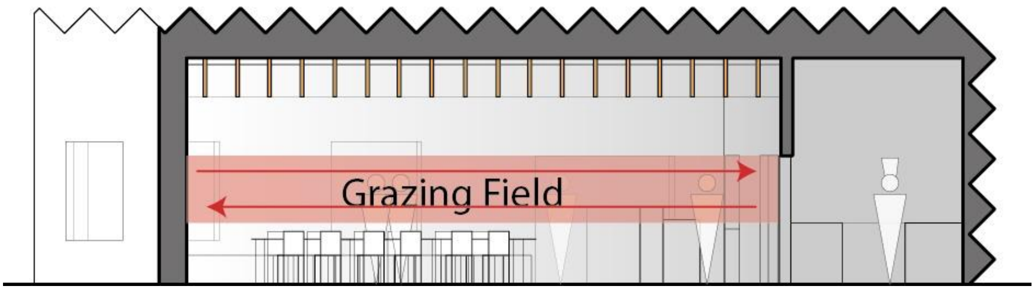

Fig. 25. The Grazing field schematically drawn in section.

A detail that adds to this problem is the fact that there's no door between the dining area and the kitchen. The sound is free to pass between the spaces. Kitchen noise is often made up of a lot of clanking and slamming – high-frequency noise – and can therefore both add to the general clamour in the dining area and disturb conversations by masking the speech sound. It also adds energy to the grazing field.

Cure

The grazing field needs to be broken up, that's the simple truth. It would also be advisable to add doors to the kitchen to keep the noise out but that might not be possible. The problem with the walls isn't necessarily their material and flatness but could also be the fact that they're all vertical – perpendicular to the floor and parallel to each other. By leaning the walls (or one of them) outwards, the one- or two-dimensional grazing field can be broken by using the specular reflections to direct the sound towards the floor or the ceiling.

Fig. 26 shows the principle of a leaning wall. A practical example is Umeå Bus Station, shown in Fig. 5. This is a geometrical way of redirecting sound. The total amount of energy in steady state will be the same. Since the walls at the restaurant are already built, this solution is not practical here.

Fig. 25 & Fig. 26 can also be used to point out that conference rooms shouldn't have hard and parallel walls. The classical solution of having parallel grass walls with a conference table in between yields very poor acoustic performance. Occasionally, a "fluttering echo" will spring up. That is a local reverberation which is very powerful and sounds a bit like some loose metal part that is vibrating. It's extremely annoying.

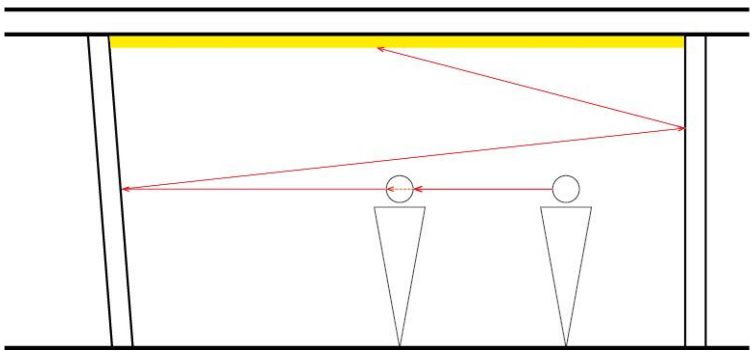

Fig. 26. Leaning one of the walls 5 degrees or so is an excellent way of breaking up the grazing field.

Fig. 27 shows four other ways of counteracting the grazing field. The first one is a set of triangles which can be designed according to principles discussed in Trevor Cox and Peter D'Antonio's book "Acoustic Absorbers & Diffusers"[4]. The second one is a cross-section of a QRD-diffuser. This is a series of boxes and gaps that follow a mathematical system known as the "quadratic residue" (see Fig. 18). The third is a less optimized but perhaps more practical version of the pyramids and the fourth is a simple wall-mounted absorber. The point with all of these is that they can be fitted on the walls in head-height, to divert the speech-sound from the grazing field. Thus, fitting these very high or very low on the wall won't work as well as fitting them in the middle.

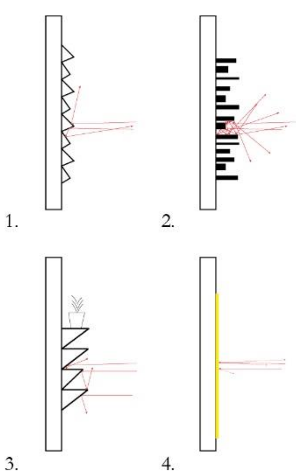

Fig. 27. Different strategies to break up the grazing field. 1. Pyramids. 2. Quadratic Residue Diffuser. 3. Triangles with flat tops. 4. Porous absorber.

This work isn't about designing a finished acoustic treatment to the room, but to show that different approaches are possible. What might be done, is to allow one of the "panels" described in Fig. 27 to circle the room and create a sort of lining to the room, which would also connect

4 (Cox & D'Antonio, 2004)

Fig. 28. Acoustic/sound-absorbing panel with print. Photo: Akustiktryck AB.

the different stretches of wall to each other. It might be covered with a linen cloth and note make much of its own presence, or it might have a print on it consisting of all the sketches that the architects made during the design process. An artist might be engaged to design a handsome textile covering. That choice belongs to the architect.

Fig. 28 shows an example of a more sophisticated acoustic wall-panel. A regular panel has been refined by adding a print that makes it play the role of a painting as much as an acoustic panel. This example is from an Italian restaurant in Gothenburg and the placement of the “picture” is the correct one to break up the grazing field. It would, of course, also be possible to combine something like this with lighting, either standard products or custom-made frames. Given the dining area at Skissernas Museum, with its surface properties and open kitchen, I would probably recommend using absorbers on the walls but if aesthetic or other reasonings make this impossible some form of diffuser could be used. This way, the acoustic properties of the restaurant can contribute to the comfort and sense of atmosphere that is the rooms potential.

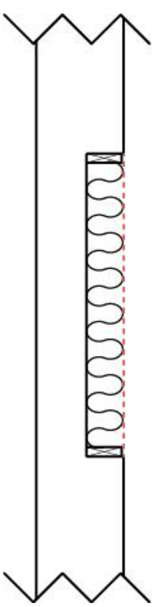

Fig. 29. An absorber could be set into the wall, with an absorbing material behind some form of textile covering.

Fig. 29 shows an alternative method, where the absorber is sunk into the wall instead of sitting on it. If this solution is planned from the start, it becomes possible to design the textile cover so that it adds something to the room without sticking out into it. This arrangement has to be fitted at the height where the users heads normally are, if it’s to have the desired effect.

What I’m suggesting here is that some minor changes to the rooms appearance could make a fundamental difference to the perceived atmosphere and increase the comfort of the visitors. Retrofitting is probably less elegant than making it a part of the original design.

Final notes

So, this project is coming to an end. The original idea was to examine more in depth how different types of diffusers and other geometrical strategies could be used architecturally. As the project proceeded however, it became clear that a more fundamental discussion about architectural sound had to precede it. So that's what I've been doing. The purpose of this Master's Thesis is to introduce sound into the architectural discourse. There's much to be gained by making acoustic engineering follow as a consequence of an artistic discussion, rather than considering sound as a mere technicality.

I've touched on the subject of sound in literature, mostly to show that non-architects are sometimes aware of and always influenced by what they hear. Architecture makes the world inhabitable for our minds and bodies. Different people have different ways of inhabiting space but what we have in common is that we have several senses with which to perceive both the world, each other and ourselves.

What this work has shown me quite clearly is that it has only started. I've been unable to find a book that digs deeper into the artistic and/or humanistic aspects of architectural sound. There are many books about architectural acoustics but these are rarely written in a language that makes them accessible to architects. This thesis could be described as a first step towards such a book. We need to find a language and a way of communicating sonic experiences in architecture. I've looked for such a language in the different places described and found that each has something to contribute. Word and thought could be said to be the same thing and therefore conscious thought can't exist without words.

The acoustic phenomena described in this text are some of the most fundamental principles in room acoustics. Using them as a comprehensive design guide is not at all advisable. The primary function, as I see it, is to give the reader some basic knowledge to help in the discussions with acousticians. My personal opinion is that this should be taught (at least as an elective) at the schools of architecture as an integrated part of the architectural expression.

Finally, I'd like to come back to what I said in the beginning. Designing room acoustics is a bit like designing and building guitars – the artistic/humanistic idea has to come first. When technology is a slave to the human mind and nature, it gives meaning.

Suggestions for further research

- Collect examples and explain why they work in terms of visual aesthetics and acoustic behaviour.
- Develop the thoughts about how architectural sound affects the aesthetic value of spaces and places.
- Use the concept of this report as basis for a book that teaches acoustics to architectural students in a relevant and accessible way.
- Investigate how the measurable parameters correlate to perceived spatial qualities in different types of rooms.
- Develop a vocabulary for architectural sound.

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Pictures

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Artistic aspects of architectural sound

Tim Elfström, 2018

AAHM01: Examensarbete i arkitektur/Degree Project in Architecture; LTH

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Summary

Tim Elfström is a luthier and student of the inner workings of soundwaves as they relate to artistic expression and architectural experience. This thesis is part of a larger process of thought about how sound is part of the architectural expression. A main point is that architects have much to gain by learning some fundamentals about room acoustics and applying the knowledge early in their design processes.

There's a difference between architectural acoustics and architectural sound. Acoustics is an engineering discipline, based in physics. Sound, on the other hand, is a humanistic and artistic aspect of the architectural experience. This thesis outlines a way of considering and designing architectural sound, where technology is made the slave of the human imagination.

The main components of the text are:

- A luthier's thoughts about the artistic aspects of sound.
- A pair of architectural theoreticians' thoughts on the importance of sound.
- Sound in novels – non-architects writing.
- Basic room-acoustics theory
- Case Study – Skissernas Museum's restaurant, Lund.
- Final notes and thoughts about further research.

The technical chapter is necessary to maintain the connection with reality. Many writings about architecture are fine in themselves but offer little or no guidance as to how their different ideals could be realised. This is, of course, more true about some texts than others but, on the whole, the connection between engineering acoustics and architectural aesthetic expression is hardly ever discussed. So, that's what I've been doing.