Research that resonates

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INAUGURAL LECTURE

Research that Resonates

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DEPARTMENT OF THE BUILT ENVIRONMENT

INAUGURAL LECTURE PROF.DR.IR. MAARTEN HORNIKX

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Building Acoustics and me

Dear Rector Magnificus, family, friends and colleagues,

I enjoyed several disciplines during the first years of my studies in Architecture, Building and Planning here at Eindhoven University of Technology, but it was not until the third year of my studies that an excitement began which has not yet stopped. At that time, I was carrying out a minor project in room acoustics with the aim of quantifying the spaciousness of a concert hall. How on earth could we rate the acoustic quality of such a space when sound varies so much across time, frequency, space and direction? The problem was far more complicated than I could solve in my minor project, despite my immense efforts to grasp it. Acoustics somehow became magical to me, and it still is. Since then, I have worked with acoustics as a student and academic.
What is it that interests me? Firstly, there is the physics of sound, leading to highly spatial and time-dependent sound and vibration fields for our audible frequency range of 20 to 20,000 Hz. Sound propagation indoors and outdoors is a branch of fluid mechanics with distinct features, as shown in Figure 1.

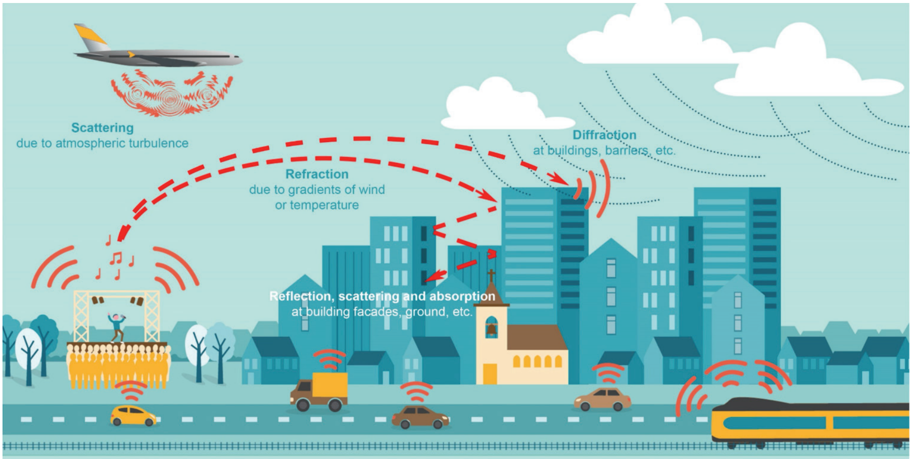

Figure 1. Features of outdoor sound propagation, all features apart from refraction also hold for sound indoors[1].

[1] Figure modified after infographic of NWO project 14275: Tools to tackle environmental health problems, https://www.nwo.nl/en/cases/how-wind-affects-sound.

- Reflection and absorption by materials ranging from an acoustically hard concrete surface to an acoustically soft forest ground.
- Scattering phenomena occurring from sub-wavelength geometrical dimensions such as rough surfaces, small objects like tree stems or atmospheric turbulence.
- Diffraction due to material discontinuities such as noise barrier tops.
- Refraction (bending of sound waves) due, for example, to inhomogeneous temperature distributions in the atmosphere.
- Attenuation of sound in gases due to viscous, thermal and molecular losses.

Sound moving through building elements is a branch of solid mechanics with distinct features as well:

- Different wave types due to the elastic properties of solid materials with their finite dimensions.
- Reflection and transmission of vibrations at material interfaces and connections, including conversion of wave types.
- Transmission of sound through building elements, partly due to the radiation of the waves in the solid structures. The interplay of sound in air and vibration in building elements, known as structural acoustics, is crucial to the propagation of sound within buildings.

The combination of the above effects with geometrical properties of spaces and structures leads to effects such as resonances in rooms and building elements, focusing effects under a dome ceiling, whispering galleries and bandgap transmission loss of periodic structures. Finally, the morphology of our heads and ears highly influences the sounds that reach us. Would we be able to reproduce all this for typical engineering problems in the built environment? This question brought me to computational acoustics, to which I have devoted many years of my career thus far.
I was also captivated by the area of signal processing: since the analysis of sound is about signals, digitally processing or computing them implies that we need to discretize signals. How can we benefit from signal processing theories such as the spherical Fourier transform in order to help reduce the complexity of computational acoustics problems?
Simultaneously, the relationship of sound to humans caught my interest. In addition to my passion for understanding and modeling the physics of sound, I became increasingly aware that the solving of acoustic problems must be related to how people perceive sound, meaning that we must always tune our computational acoustics approach to perceptual resolutions in terms of frequency, time and direction. Sound as a source of information in spatial perception holds a particular

interest for me, especially the use of sound for navigation and cognitive mapping in blind people. Foremost, I have also developed a permanent determination to raise public awareness of the adverse health effects of sound, a serious societal problem. Finally, I am convinced that the societal problems and opportunities associated with building acoustics can only be handled by well-trained engineers. They must be equipped with knowledge, skills and a problem-solving attitude in order to be prepared for the current and future challenges that will arise.
All this sums up the drivers for my academic career: acoustics for science, society and students.
I will first take you to the impact of sound on society, then I will give an overview of our Building Acoustics research group. After this, we'll dive into the research approaches and research areas we cover. Finally, I will shed light on the future of our research and my view on the context here at TU/e.

Sound and society

We might be not continuously aware of it, but sound is everywhere around us at all times in the built environment. Even so, there is so much sound around us that sounds are more notable when we are in a very quiet environment. This sometimes happens to me during vacations abroad in the mountains. When I arrive at our destination, one of the first things I notice when I get out of the car is the absence of a blanket of background noise. Instead, it is quiet and peaceful and subtle sounds capture my attention: the small pebbles crunching under my feet as I walk, the single car driving down a secondary road in the valley below or a couple of birds singing to each other. Sound is created by sources of sound caused by nature or induced by humans. It is a carrier of information: it is essential in communication and can be a warning of threatening situations. And it is enjoyable – who doesn't love music? At the same time, it can also be a serious threat to our health. Unwanted sound, which we call noise, is the second most significant environmental cause of ill health in western Europe, behind air pollution. Chronic exposure to environmental noise from road, rail, aircraft and industry sources has significant impacts on physical and mental health and well-being, causing annoyance, cardiovascular disease, sleep disturbance and associated effects such as loss of cognitive performance. Exposure to environmental noise is a widespread problem in Europe, with at least one in five people exposed to levels considered harmful to health [1]. In European territory, it is estimated that 22 million people suffered chronic high annoyance and 6.5 million people suffered chronic high sleep disturbance in 2020. And long-term exposure to environmental noise is estimated to cause 12,000 premature deaths and contribute to 48,000 new cases of ischemic heart disease per year. What is more worrying is that the number of people exposed to high levels of (road traffic) noise remains high and is likely to increase in the future because of future urban growth and an increased demand for mobility.

Next to the environmental noise problem, current problems in buildings are related to low-frequency sounds (humming sounds) from neighbors, especially in lightweight buildings, and sounds in open plan offices and study environments. This is in addition to the ever-present challenge of creating sound environments that support their functions, such as music, speech transmission, speech privacy or (a quiet environment for) studying purposes.

Due to several reasons, acoustics and noise are rarely a main topic on (inter)-national research agendas but typically come into the picture as a consequence of other developments or choices, such as noise that comes with the development of new ways of heating our houses or the impact of planning a new airport. It is therefore important to keep stressing the impact of noise, as is currently being practiced in the Netherlands by *Stichting Klankbord*.

Many people are working daily on creating good sound environments in the built environment: acoustic consultants that participate in design teams of new buildings or provide consultancy work to ensure that acoustic standards are adhered to when new roads are planned, policy advisors in local or national public authorities, manufacturers of acoustic materials to provide sound absorption or insulation, companies that develop calculation and measurement software to support consultants with their work, or companies in the automotive or audio industries.
These people know which sound-related problems exist in society, what opportunities exist, how legislation is protecting our society and how it is not protecting us and how measurements and prediction tools should be used. They also know what we cannot measure or predict properly. I am grateful for all these engineers – professionals – that do their utmost best each day to provide a better sounding world.

Building Acoustics: the research group

SCIENCE OF SOUND

To address the above societal challenges related to sound, we need a good understanding of the whole chain of acoustics: the generation of sound near the source (be it a car, organ pipe or voice), the propagation of sound from the source of sound to the listener and the way this sound is perceived and impacts humans. The expertise of our Building Acoustics chair lies within the second part of this chain: the quantification (either computationally or experimentally) of the influence of the built environment on sound propagation from the source to our eardrums, expressed either quantitatively or by auralization (the acoustic counterpart of visualization). Auralization means making the sound field of a source in a space audible by physical or mathematical modeling. Our activities hold for both outdoor and indoor environments, from distances of kilometers in urban areas to tenths of meters inside residential buildings and centimeters within building materials.[2] The first modern scientific methods in our fields of research arrived over a century ago, while computational approaches were initiated about half a century ago.

Some scientific challenges are still unresolved today. To name some important ones:

- Computationally reproducing the acoustics of a concert hall by solving the governing wave equation for the full audio range (that is to say, a frequency range up to 20,000 Hz) has not been achieved thus far.
- We are still looking at how to reproduce the sound field to provide a fully authentic sound experience with as little processing power as possible in a virtual reality environment.
- There are standing challenges related to acoustics materials – such as representing any kind of material as a boundary condition in computational modeling (specifically extended reacting materials) – and in the development of materials that absorb sound of all audible frequencies with a limited thickness.

[2] Without getting into a semantic discussion, the field of Building Acoustics, as known to the acoustics community, has a more limited scope than the coverage of research areas in our research group.

MY VISION

My vision is to aim for a high acoustic quality in the built environment at all times, which must be free from adverse health effects due to noise. This does not necessarily imply a noise control approach, meaning the classical approach to reducing noise, as health conditions can also be improved by securing access to areas of high acoustic quality and deploying a soundscape approach. New sources of sound continuously arise, such as wind turbines and drones, as well as new building concepts. This faces our Building Acoustics chair with the ever-present call for up-to-date knowledge, tools and products to be able to secure a healthy environment with respect to sound. The education of students who are able to face societal problems involving acoustics is part of this.

My research revolves around the continuous development of in-depth computational methods to quantify the acoustics of the built environment: its influence on the propagation of sound from the sources to our ears. The aims of these developments are threefold:
1. Contributing to answering open scientific questions in my field of research.
2. Supporting thematic research on understanding the mechanisms of sound and its perception in the built environment and developing solution strategies.
3. Providing researchers and designers with tools to integrate and optimize acoustics for the (re)design of the built environment.

The research areas in our group are virtual acoustics, environmental acoustics, acoustic materials and the effects of the sound environment on humans, see Figure 2. My expertise is mostly in the first two areas.

OUR EDUCATION

Because sound has a major impact on society, industry and government agencies are constantly asking for graduates in acoustics for a variety of jobs. We train students at all levels of academic education, at a bachelor's and master's level as well as at a post-master's level. In addition to the courses developed for students in our own department who eventually graduate from our research group, it is important to note that the vast majority of students who take our required courses in the undergraduate program end up somewhere else in the Architecture, Engineering and Construction (AEC) industry. For example as architects or

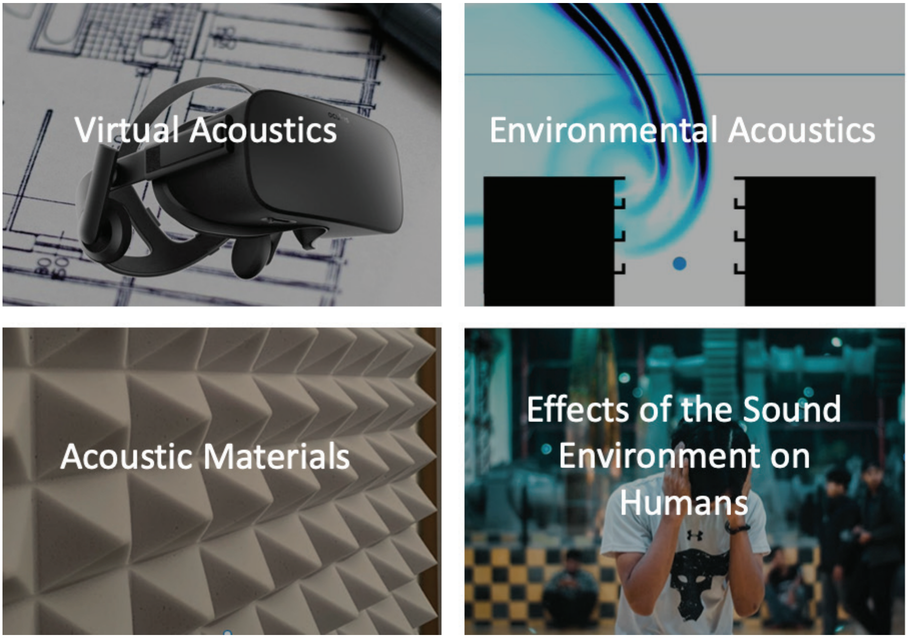

Figure 2. Research areas of the Building Acoustics research group.

structural engineers. Conveying the relevance of sound in and around buildings and the basic knowledge of building acoustics is important. For this purpose, we have recently developed a VR platform where students can intuitively experience the effect of changes in the dimensions and materials of spaces on the sound of speech or music in that space. Since 2013, I have been coordinating an elective coherent course series called the Science of Sound and Music for all students at our university, to which four other TU/e departments have contributed. This past year, we lectured to an average of 40 students per course. At the post-master's level, we have been involved in two European doctoral training networks, one of them as coordinator (Acoutect), for which we have created new training programs. The YouTube channel of the doctoral students reflects their learning curve. Starting next year, we will organize an Autumn School Series in Acoustics (ASSA) at a doctoral level here in Eindhoven, where we will teach PhD students fundamental and applied topics on acoustics (Figure 3).

Figure 3. The Building Acoustics research group will organize ASSA, a yearly one-week international PhD school in Acoustics, https://assaeindhoven.org.

Together with the digital learning platform for building acoustics that my colleague Dr. Jieun Yang will develop, there is plenty to look forward to regarding our education.

A NOTE ON IMPACT

Sharing our group's research results is part of the value we want to resonate on the impact of sound, but this is mainly limited to the scientific community. Reaching out to a wider public on why, what and how we work is a part of that too. Being a research group on acoustics of the built environment also implies taking roles on interpreting or clarifying situations related to sound and noise that arise in society, as well as making what we do in our group visible. I wholeheartedly support open science initiatives related to open source software. To that end, it is also important to share the tools we develop; in our case, mostly simulation and virtual reality software. We have launched the PSTD software on sound propagation as an open source project, see Figure 4, with the code in GitHub and the software on a dedicated website with documentation, including the more than 30 papers we have written about it. We've learned that this is valuable (>1500 downloads), but the goal of creating a community around it has not gotten off the ground yet. A direction we have recently taken is to launch our software via a website and the TU/e GitLab. The presentation of our software will now also be accompanied by instruction videos along with the software code itself.

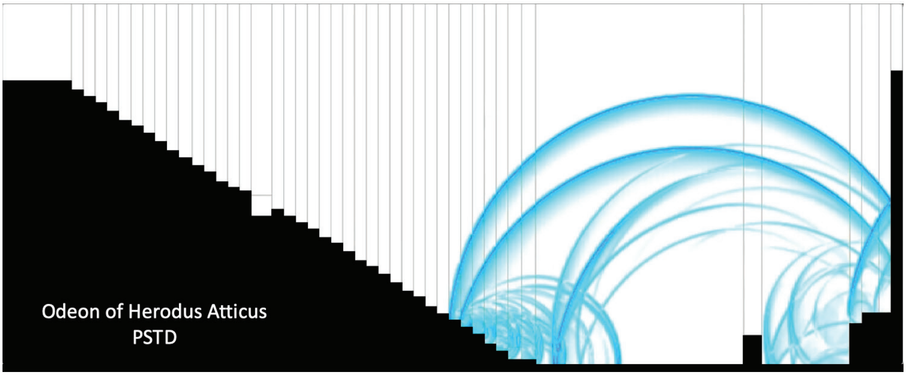

Figure 4. Snapshot of sound propagation in a cross section of the Odeon of Herodus Atticus theater, calculated with the openPSTD software. Grey lines denote the subdomains of the calculation model.

Computational acoustics: complexity and approaches

CHARACTERISTICS OF BUILDING ACOUSTICS IMPULSE RESPONSES

Let's now take the opportunity to immerse you in our research arena. In building acoustics, as in other fields of physics, experimental and computational tools are instrumental to advancing scientific knowledge and its impact on societal problems. Experimental methods are needed as they capture what happens in the real world, thereby allowing us to rate the acoustic performance of spaces and building elements as they are. They are also needed to validate results from computational methods, such as to make sure that the acoustic specifications of a freshly inaugurated concert hall follow predictions. Furthermore, experiments in laboratory conditions help to quantify the acoustic properties of building materials and elements outside of their contexts. On the other hand, computational methods are highly necessary: predictions are needed to assess and optimize the acoustic quality of new buildings, redesigns of buildings and plans for new (sub)urban infrastructure. Also, computational methods are needed in product development, such as for sound absorption and insulation materials.

A common thread through all of our areas of research is the characterization of the acoustic transfer path between two points in space (source and receiver), which is called the impulse response when the signal is expressed as a function of time and the transfer function when expressed as a function of frequency. Mathematically speaking these are the Green's functions. Consider Figure 5. At the bottom, you see a typical impulse response of a room, a sports hall in this case, in which the first spike is the first sound that arrives at the listener due to the impulse made by the source of sound. The subsequent pressure values in time are due to all interactions of the sound (as reflections, scattering and diffraction) with the boundaries and the objects with their acoustic properties in the room. The time signal that you would hear in this space is binaural, meaning a signal in the left and right ear; on top of this impulse response, there is thus the head-related transfer function (HRTF) of you as a person, which is unique. Besides characterizing the space acoustically, the impulse response can be used to make any sound in this space audible (given that source directivity is taken care of).

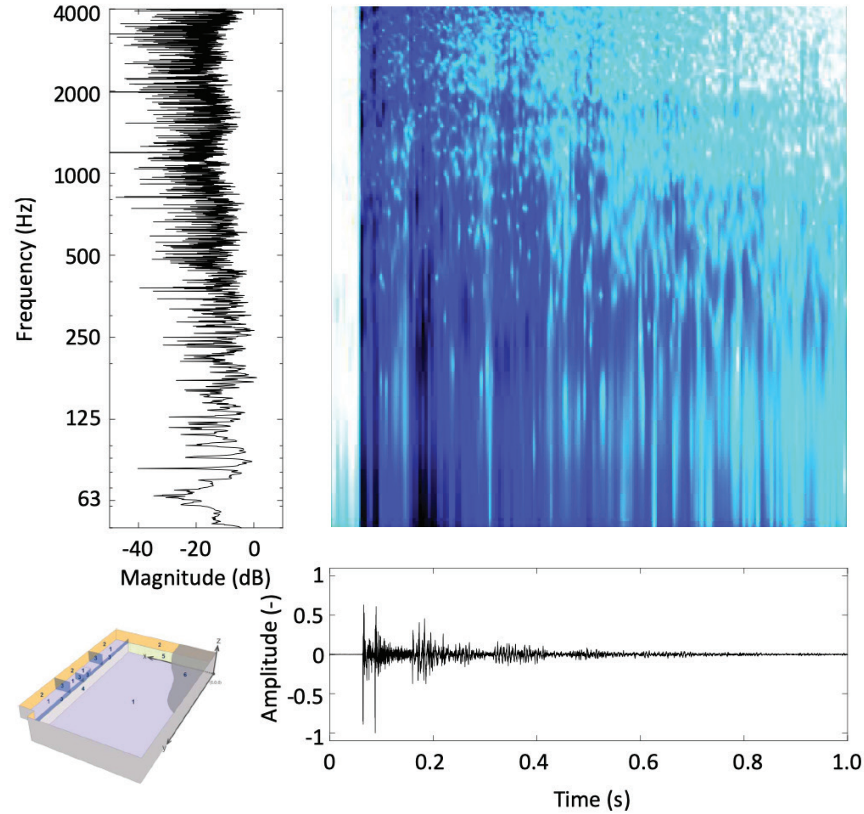

Figure 5. Acoustic characterization of the sound field in a sports hall [2]. Bottom: impulse response, top right: spectrogram, top left: frequency response.

The time signal can be decomposed into its frequency components on a spectrogram, the colorful picture. There, you can see that the behavior of sound is dependent on time and frequency. The characteristics of indoor spaces are that the sound field is clearly composed of distinct frequency components (resonances or room modes) at low frequencies, whereas the sound field becomes more homogeneous over frequency (and space) at higher frequencies due to an increase of the modal density. A critical aspect is the coherence of sound: there is high coherence at low frequencies and early times, but the coherence drops and the field turns incoherent when time and frequency increase.

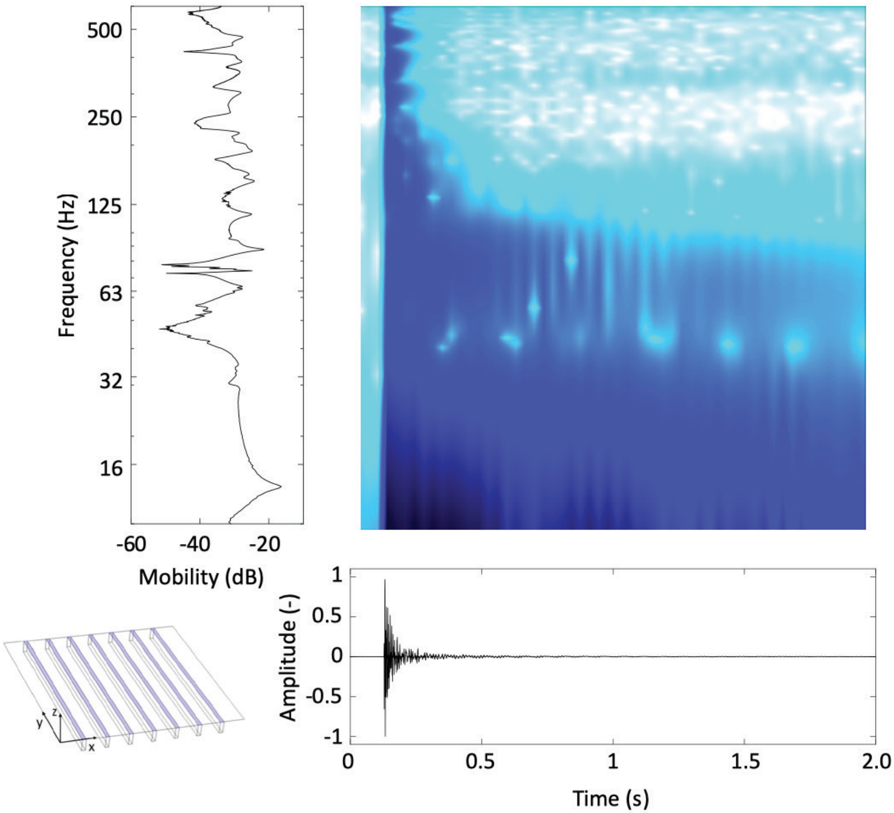

Figure 6. Acoustic characterization of the vibrational field in a wooden floor [2]. Bottom: impulse response, top right: spectrogram, top left: mobility.

To reproduce this sound field completely, a solution to the governing equations of fluid dynamics (wave equation for room acoustics) is needed. However, the simplification of modeling approaches is possible for some parts of our spectrogram. At high frequencies and late time, the sound field is incoherent and a model that solves only the incoherent sound field (such as the diffusion equation) could be sufficient. Furthermore, at high frequencies, when the wavelengths of sound are small and the sound behavior mimics light rays, the early time of the impulse response can be captured by an image source model. The computational reconstruction of the sound field is one of the challenges that we face in our research field, which is also dependent on the room type, sound source type and purpose of reproducing the sound; a model that needs to reproduce an overall sound pressure level in decibels to estimate noise exposure is different to a study that needs to reproduce the impulse response of a lecture room for auralization purposes.

A similar result for a structural acoustics problem (hitting a floor at a point force) can be seen in Figure 6. Again, we have a time response of the vibration field in the floor and a similar story on the coherence of the sound field can be told here. Whereas the physics is different (as the medium has significant elastic properties and the damping mechanisms of vibration are different), the rationale for solving the governing equations in the low-frequency range and the consideration of the incoherent field at high frequencies does hold here.

Finally, an impulse response may look somehow different for outdoor sound propagation. For example, sound propagation over a flat ground surface in the presence of wind typically consists of a lower number of contributions in time than indoors or in building elements as only the direct sound and ground reflections are present. The dips in the frequency responses are now governed by the interferences of sound waves directly reaching the receiver and responses that arrive via one or multiple reflections via the ground surface.

COMPUTATIONAL METHODS

To reproduce sound and vibration fields, we need to have a model that represents the physics (typically expressed by partial differential equations) and we need computational methods to solve these equations. The development of computational methods has been an expertise of our research group throughout the years. Driven by the need to understand physical processes in building acoustics and to reduce the burden of the excessive calculation times, we have been working on approaches that provide accurate results at faster computational speeds. Typically, about 10 degrees of freedom per acoustic wavelength are required to solve the governing partial differential equations for acoustics in spaces via a classical computational method like the finite element method (FEM). For the big concert hall of the Muziekgebouw in Eindhoven, about 14,400 m^3, this means three trillion degrees of freedom to solve in space, and the solution has to be marched in time by 600,000 time steps. Other computational methods or simplification of the models that mimic physics are needed, where possible, to make full audio calculations doable!

An adopted strategy since my PhD time has been to make use of wave information (fundamental solution components of the governing equations) in the computational method itself. To that end, I further developed the pseudo-spectral time-domain (PSTD) method for problems in indoor and outdoor acoustics. This approach solves the governing fluid dynamics equations and only requires 2.5 points per wavelength, reducing the number of degrees of freedom by a factor of 64. Still, solving the Muziekgebouw would need 4.5 billion degrees of freedom.
The key aspect of PSTD is that it transforms the spatial solution to the wave number domain using spectral basis functions that together compose the sound field, evaluate the spatial derivative operator in the wavenumber domain, and return to the spatial domain.
The PSTD method has been used in various applications, such as computing the sound field in a sports hall, calculating the effect of vegetated facades and green roofs on the propagation of urban noise to urban courtyards, calculating the influence of meteorological effects on sound propagation over urban areas and calculating the scattering of sound by trees [2-5], but still has limitations related to boundary shape and properties. We have therefore devoted efforts to further developing a modern FEM method, the Discontinuous Galerkin method, with the main reason being that this method allows us to solve any building acoustics problem we want and can be accelerated by modern computer architectures as computational operations are mostly local per element [6].
In this methodological research, I have collaborated with Dr. Roger Waxler, a Mathematical Physicist from the University of Mississippi, on the PSTD method. Regarding the DG method, we are in close collaboration with the Technical University of Denmark and the Iceland-based start-up Treble Technologies.

Research areas and our approaches

Following this introduction to the characteristics of building acoustics impulse responses and computational acoustics approaches, I will take you to our research areas, their relevance, our research approach and how we collaborate in this research. We currently have four research areas, for which I will each pick out a project to demonstrate our way of working.

ACOUSTIC VIRTUAL REALITY

A technology that is rapidly emerging in the built environment is the use of mixed reality (MR) technologies to experience designed scenarios of spaces and buildings. Virtual Reality (VR), as a form of MR technology, offers a wide range of opportunities for the acoustic community: acoustic consultants can use it as a tool to communicate the acoustic consequences of design choices with architects (such as spaces becoming hard to use for speech communication) and residents may virtually experience how an envisaged noise barrier will change the sound environment outside their homes. What we need is technology that offers an acoustic perception that matches the prospective or real environment. The complexity of reproducing sound in VR lies in the real-time reproduction of sound to a listener who can rotate its head, move and even speak in the environment while other sound sources in the space may move as well.
Our approach is to first develop a reproduction of the acoustics in VR based on computational acoustics with the aim of using this as a benchmark for further research. The perceptual experience of the VR environment based on both acoustic measurements and acoustic predictions solving the governing fluid dynamics equations (wave equation) is used to create this baseline. To reproduce the binaural signals at any possible angle from one calculation, we make use of spherical harmonics [7].
To rate the perceptual difference between measured and predicted signals, we question the participants in our listening booth on the feeling of being immersed and the perceived reverberance, among other things. The approach requires full control over both measured and simulated scenarios involving material characterization, signal processing and source characteristics. The follow-up work is to use a simplified computational approach that allows for a full audio reproduction

but that renders a highly similar experience to using the full simulation, which is the solution to the wave equation. It follows the rationale of solving different parts of the spectrogram with different computational models that are suitable for this time-frequency space. What is challenging here is the balance of efficiency in calculations while offering the appropriate perceptual experience.
For this research, we collaborate with Facebook Reality Labs (Oculus VR) and the HTI group of our university via Emeritus Professor Armin Kohlrausch.

ENVIRONMENTAL ACOUSTICS

Noise that propagates from environmental noise sources, such as road and rail traffic, aircraft and wind turbines, is influenced by meteorological effects in the lower part of the atmosphere. This causes that, despite noise barriers, complete neighborhoods of cities are exposed to highway noise. It also causes that a significant part of a city can experience loud music from an urban festival, or that the runway noise from aircrafts is clearly audible on a clear summer morning.
In the NWO project *Tools to tackle environmental noise problems*, we have addressed these issues in the following way. The effect behind the aforementioned problems is only partially addressed in our research community. Urban sound propagation, including wind and temperature effects over complex areas, has hardly been studied due to the combination of complex phenomena which are hard to model efficiently: the topology of the built environment and its material properties as well as the meteorological conditions, which are the time and space-dependent wind and temperature fields. A propagation model solving the governing fluid dynamics equations (linearized Euler equations) is needed to investigate the wind effect on sound in a complex topology, but that typically requires long calculation times with conventional computational solvers. We have coupled the two aforementioned computational methods spatially (PSTD and DG), marrying their favorable properties: PSTD is efficient in unbounded media and DG is state-of-the-art in complex topology situations. In a parallel project, the boundary conditions in DG were developed so that we could use them in this project. The method is now used to study the effects of a solar panel field along highways on the sound propagating to neighboring areas, a practical question that engineers need to solve but lack tools for. Our method is being validated by acoustic measurements in the wind tunnel. Besides, we have run several experimental campaigns in this project to quantify the wind effect on sound propagation along a highway, along a railway track and in a city center with church bells as the source of sound. In Figure 7, you can see how the sound level due to the A50 highway in a

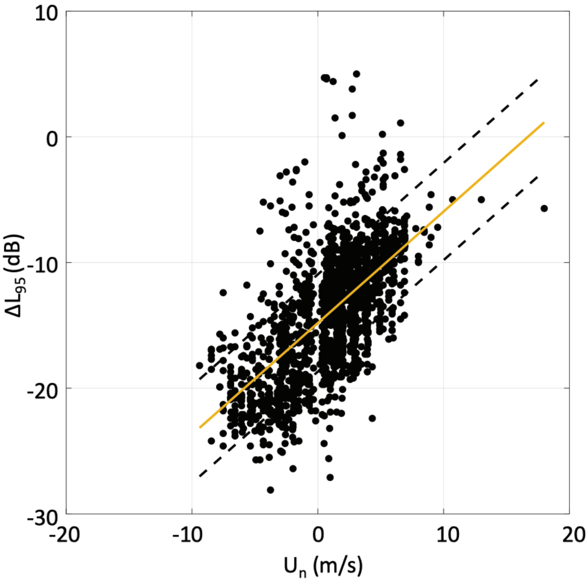

Figure 7. Influence of the average wind velocity U_n on the background sound pressure level difference ΔL_{95} (dB) in a residential area near a highway in Son. ΔL_{95} is the sound pressure level relative to the sound pressure level close to the road. U_n is the wind velocity component in the direction from highway to residential area. Data collected by Sai Trikootam.

residential area in Son increases with higher wind speeds despite the existing noise barrier. This work will pave the way to an improvement of engineering calculation rules on wind effects in cities.
In this project, a collaboration with the Building Physics group of Prof. Bert Blocken and Dr. Twan van Hooff was highly necessary given the multi-physics problem we faced. Experience from TNO and the city of Eindhoven has also assisted us in the project.

ACOUSTIC MATERIALS

Creating buildings with less material is more sustainable and wood is gaining interest as a building material. However, it is easier to excite vibrations in low-weight materials and they more easily radiate sound. The low-frequency sound of people walking on floors is particularly problematic when it comes to noise annoyance.

Our approach is to first develop a model to quantify the vibrations and radiated noise of wooden floors by developing a computational approach efficient enough to later perform many calculations in order to evaluate possible solutions. For this purpose, we use an analytical method for the modeling of the floor, solving the simplified linear elasticity equations for only the wave types that are relevant, and expand this to include a possible floating floor and a person on it. We connect this to a detailed model (the boundary element model) to calculate the radiated sound in the room underneath. Again, we have measured this scenario in our lab, for which we have adopted a novel way to excite the floor via an impact force plate in order to mimic the high impact of low-frequency sound. This model now allows us to quantify possible solution scenarios, of which an optimal set of vibration absorbers underneath the floor seem a promising path. In Figure 8, you can see the reduction of sound in the low-frequency range for an additional 10% of material weight by the vibration absorbers.
For this research, we have collaborated with Level Acoustics and Vibration, a spin-off company housed in the TU/e Echo building, and the floor construction company Vloerenbedrijf Van Rijbroek.

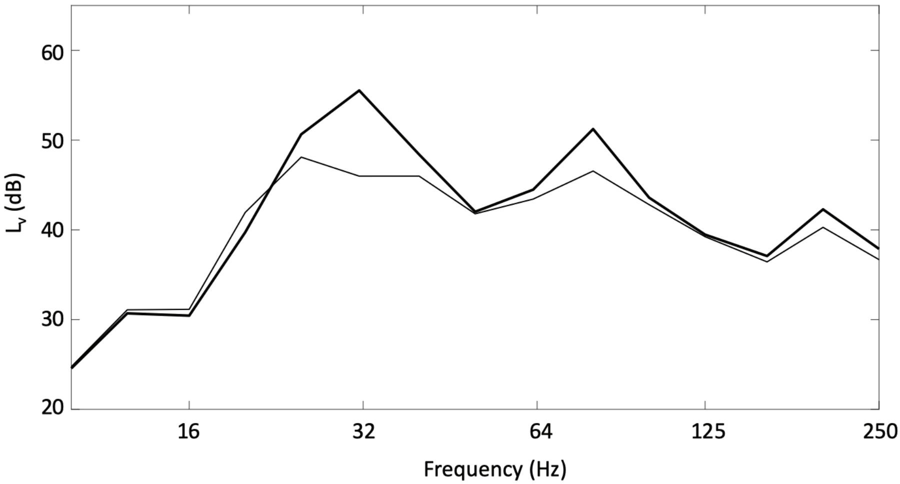

Figure 8. Vibration level in a wooden floor at low frequencies, computed with an analytical model by PhD student Yi Qin. Thick line: wooden floor, thin line: wooden floor with vibration absorbers (constituting a 10% mass increase).

EFFECTS OF THE SOUND ENVIRONMENT ON HUMANS

During one complete day, we carry out various activities while always residing in environments with sound. Research is needed on the cross-section of building acoustics and psychoacoustics in order to develop recommendations on how spaces such as canteens, open plan offices and hospitals should be designed to promote environments where user performance is not affected by sound and user health is not degraded. For such studies, the salient differences encountered in indoor sound environments and the specific tasks of the users need to be considered.
The research on this area is clearly interdisciplinary and the combination of our expertise with the expertise of Prof. Armin Kohlrausch has led to collaborative research.
In a recently-completed PhD study, Ella Braat has investigated the influence of room acoustic properties and changes in the settings of the background noise (particularly the number of students talking in the room) on the (perceived) performance of specific student tasks in open plan study environments (OPSEs) [8]. A sound environment has been recreated under laboratory conditions based on sound from loudspeakers. The simulated environment, benchmarked by measurements of that room, has then been modified to offer various sound conditions for the study. The sound environment in OPSEs has been shown to have an increased effect on the disturbance of students if the background noise comprises speech. The results show a decrease in the performance of students in their tasks due to typical sound scenarios, but not for all tasks.

What's next?

Moving forward with our research areas, I have several plans in mind that we aim to work on.

Let me start with our impact related to our tools. Our acoustic society can be characterized as rather fragmented: acoustic consultants make use of simulation tools available on the market and typically maintain good practices on the usage of simulation tools within their office, companies develop software but mostly work as stand-alone entities without being connected to universities and researchers mostly present their work to other researchers at conferences. What I propose is an active open source platform and community around acoustics software (and tools) in which researchers share contributions to flagship software (software they jointly develop and maintain), companies (as spin-offs) may branch parts of this software into commercial software for real-life problems without stopping scientific developments and consultants can utilize the developed software and communicate on their experience, thereby returning new and ongoing problems to researchers who continue to develop the software and tools; see Figure 9.

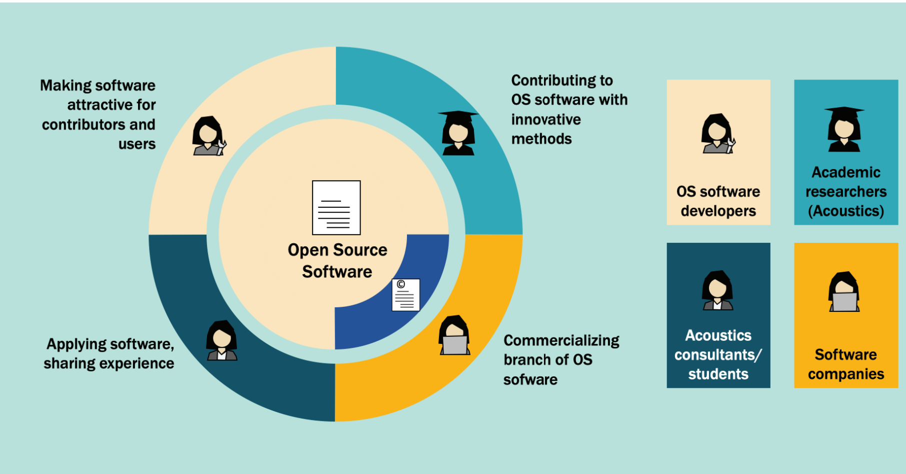

Figure 9. Targeted open source community, centered around open source acoustics software. The four member types of this community are currently not connected around simulation software.

Foremost, we need open source software developers to make the tools attractive and thereby retain users. This system would take our field further and I am ready to take a leading role in this.

In relation to our work on VR, we are targeting a fully immersive virtual or mixed reality environment where users can experience acoustics. Examples include scenarios in which you can talk with a member of your design team in the lecture hall you designed or an environment in which musicians all over the world can play together in a virtual concert hall while sitting at home. These developments should come together with haptics and visual rendering. Such an environment would be a perfect basis for research on the effects of sound on people, as much is still unexplored at that end. It will also anticipate new types of sound sources, such as electric air taxis in our cities. Without the visual part, acoustic VR and AR are also instrumental to enriching the experiences of blind people. In recent years, their toolkit has rapidly enlarged with electronic navigation aids helping them to navigate through environments with audio landmarks and spoken text, among other things. We aim to provide them with a context, namely a perception of the environment around them, via echolocation through VR or AR that makes their experience richer and more natural, and improves independence and self-confidence.

In the development towards this, we need to propose simulation methods that are time-efficient yet yield realistic perceptual rendering. In our quest, we will continue on our hybrid modeling efforts combined with signal processing approaches and will also explore machine learning methods [9]. What we end up with in these developments is in fact solving the *perceptual wave equation* for the situation at hand.

The VR and AR developments are human-centered. Whereas traditional building acoustics research focused mostly on physics, such as laboratory facilities to test the performance of building materials and elements, we now also utilize facilities which test the impact of building acoustic quantities on human performance and perception.

Our work demands collaboration with psychologists, cognitive scientists and human-computer interaction researchers.

We are also looking forward to continuing to contribute to reducing the environmental noise problem with our expertise in quantifying noise reduction measures, providing benchmark calculations for improving simplified engineering models and supporting citizen science platforms in communicating about environmental noise exposure. A path taken recently in communication on noise exposure is the generation of real-time noise maps [10] in which prediction models are fed by data from smart sensors. Such maps are also highly needed for aircraft noise exposure.

A recent opportunity related to acoustic materials is the production of materials with additive manufacturing, which offers researchers the possibility to optimize materials with respect to their absorption or transmission properties. This means using as little material as possible for the intended performance. The research is challenging as multiple wave phenomena come into play, and this challenge also involves the use of sustainable materials and collaboration with designers and structural engineers. My colleague Dr. Jieun Yang and university researcher Bram Botterman will pursue this research line.

One thing is certain: the effects of sound on our society will be different in 20 years, in part because of the change in new types of building concepts and materials, new types of vehicles and machines that produce sound and the way in which we work and live. In this changing world, we stand ready to provide the knowledge and methods needed to prevent the adverse health effects of sound and to optimize sound environments. We will continue to resonate on the impact of sound.

The university perspective

Working in academia at TU/e revolves around education and research, which is where we as academics excel. In this role, we need to collaborate and team up with colleagues from other disciplines and with industrial and governmental partners outside the university. This is very much the nature of our university. The internal character of our university has changed over the years, from mostly disciplinary entities to collaboration on strategic areas such as energy and health and to collaboration in institutes on themes. We have moved from a local university to a university with an international reach and reputation and high ambitions. But we need to keep our core strength at all times, which is excellence on innovative research and in training the engineers of the future. The impact we have through this will continue to be immense if we keep our high standards of quality, are open to industrial collaboration and welcome excellent academics and international guest researchers.

Two years ago, one month before I turned full professor, I became vice-dean of our department. As a vice-dean, I am highly committed to contributing to the creation of a departmental community of trust, freedom and collaboration. I consider the university a place where all scientific staff members have the agreed opportunity to excel in their own talents. We need to set up an environment where this is possible. At the same time, we have a joint responsibility to create impact on society. We can support each other a lot by forming a community through the sharing of experiences and good practices in research and education and giving constructive critical feedback. I embrace open science and, in my opinion, this should go hand in hand with an open community. In such a community, successes can be celebrated as successes of the community rather than of the individual alone. We are moving in the right direction and I am happy to be part of it.

Words of appreciation

Finally, I would like to express gratitude to people for having inspired, helped and supported me in my academic journey.

First of all, my life-long inspiration in acoustics was triggered by Constant Hak, my former supervisor and my colleague since 2012. Constant, thank you for always radiating your enthusiasm about our field to me and to the group! Also, I am grateful to have been a recipient of the amazing lectures of Emeritus Professor Mico Hirschberg as a student. He lectured on complex acoustic phenomena with understandable and exciting analogies.

In my eight-year period abroad as a PhD and postdoc, I not only became a skilled and independent researcher but also learned how to develop and manage an acoustics research group, both content-wise and team-wise. I am therefore grateful to Wolfgang Kropp and Wim Desmet. For the improvement of my scientific skills in acoustics, I am thankful to my PhD supervisor Jens Forssén, who also taught me to be patient, and to Roger Waxler, who was so kind to host me for a research period in Mississippi.

Ten years ago, I had my presentation for the recruitment committee of the Department of the Built Environment. Without the efforts of the late Professor Renz van Luxemburg, I would not have been recruited. We only worked together for one single month and I will never forget your words: “nu moet je het gaan waarmaken.” Renz, you are with us today.
As an assistant professor, Bert Blocken took responsibility for me. Despite the sky-high ambitions he has for his own research field, he had confidence, appreciation and wise words for me. These conditions were exactly what I needed at that time in order to develop as a researcher and build our research group.

The formal start of my career as a full professor almost coincided with the retirement of a colleague with whom I have collaborated the most at TU/e, Armin Kohlrausch. This collaboration connected the world of computational acoustics and psychoacoustics, leading to joint research impact. Armin, thank you for that wonderful time, both content-wise and as a pleasant colleague, and I hope that we keep on collaborating, albeit at a different level of intensity.

I am thankful to all members and former members of the Building Acoustics group and Level Acoustics and Vibration ever since I started working as an assistant professor. As is typical for university research groups, many members come and go, with the benefit of lasting international collaborations and good friendships. My first two PhD students started in 2013, Raúl and Fotis, and although I became a father in 2017, they somehow feel like my first kids. They graduated and work abroad now. Guys, thanks for the time together. This time won't come back but our relationship remains!

Two years ago, I started as a vice-dean. This has put me in a wonderful position to be able to contribute to the challenges we face and opportunities we have in our department. I am grateful to Theo Salet for offering me this opportunity.

Research and education is not possible without good support. A huge thank you to all the support staff I have worked with during my career.

Ook buiten de universiteit zijn er enkele belangrijke krachten voor mij, die me hebben gebracht waar ik nu sta. Mijn broer en zus, Jos en Katrien, dank jullie wel. Aan mijn ouders, heel erg bedankt dat jullie me mijn hele leven in mijn keuzes gesteund hebben.
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Last but not least, aan mijn twee meisjes, Lydia en Louise: dank dat jullie je leven met mij delen en we samen leuke dingen doen die mijn leven nog kleurrijker maken.

Ik heb gezegd.

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Curriculum vitae

Prof.dr.ir. Maarten Hornikx was appointed full-time professor of Building Acoustics at the Department of the Built Environment at Eindhoven University of Technology (TU/e) on July 1, 2019.

Maarten Hornikx (1980) obtained his MSc in Architecture, Building and Planning with a graduation project in Building Acoustics (2004) and his PhD in Applied Acoustics from Chalmers University of Technology (2009). Hornikx received a Marie Curie IF grant to conduct postdoctoral research at KU Leuven (2009-2011), worked as a part-time senior researcher at Chalmers (2011-2013) and returned to Eindhoven University of Technology in 2012 as an assistant professor and then turned associate professor (2017) at the Department of Built Environment. Hornikx received another individual grant (Marie Curie Career Integration Grant) in 2012. At TU/e, he leads the Building Acoustics research group and coordinates the coherent course series Science of Sound and Music (since 2013). He has been the coordinator of the H2020-ITN project Acoutect. Since 2019, Hornikx has been vice-dean of the Department of the Built Environment and serves as the scientific director of the 4TU.Built Environment Center (2020-2021). Internationally, he has served as the chair of the Computational Acoustics Technical Committee of the European Acoustics Association and is Associate Editor of the association's journal, Acta Acustica.

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