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The start of acoustic research at Chalmers University of Technology

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Abstract – At the beginning of the 20th century building acoustics developed from a more empirical field to a fully developed sub-discipline in acoustics. This was supported by the development of measurement techniques required for carrying out laboratory and field measurements and by people engaged in building up acoustic laboratories. So also happened in Sweden in the middle of the forties when Per Brüel came to Chalmers University of Technology where he started the Chalmers Acoustic Laboratory. He was soon joined by Uno Ingård who later was professor at the MIT. At that time Sweden was in a transformation process from an agrarian to a highly industrialized nation leading to a large urbanization. Shortage of housing and the need to increase housing standard led to the so-called million programme with the goal to build one million flats. New building technologies led however to buildings of varying acoustic quality. As consequence building acoustics was identified as an important part in the education of civil engineers. In 1962 Chalmers established a professorship in building acoustics. In 1969 Tor Kihlman became the first professor in building acoustics in Sweden. That was the start of Applied Acoustics at Chalmers University of Technology.

Keywords. History in acoustic, Building acoustics, Acoustic measurement techniques

1 Introduction

The work behind this paper is driven by the interest how acoustic research activities started at Chalmers University of Technology in the beginning of the 20 century. While scientific achievements are typically well documented by publications, the historical background leading to the establishment of a discipline at an university is easily forgotten, although one hardly can separate both. The paper therefore focuses on the circumstances which led to the start of Applied Acoustics at Chalmers University of Technology in 1969 as an institute with strong focus on building acoustics. Section 2 describes the background in a socio-economic context in Sweden during the first half of the 20th century relevant for the area of building acoustics. At that time building acoustics was in a state of transition. For this, empirical knowledge had to be combined with understanding of the underlying physics. Subjective judgment needed to be replaced by objective measured quantities. The advances in electrical engineering were the fundament for starting acoustic laboratories and by this systematic research in acoustics.

The development of a new discipline, however, not only needs a clear motivation and the technical

possibilities, but also talented people full of scientific curiosity willing to enter terra incognita. Those people met just by chance at Chalmers in the forties and fifties of the 20th century as described in Section 3. This section also contains a description of the very first acoustic laboratory at Chalmers.

While previous section made the attempt to explain the historical background to the start of the Institute of Applied Acoustics in 1969, Section 4 briefly report what has become of the institute from todays perspective.

The paper is concluded with some general remarks on what can be learned from a history of a discipline from such a distance point of time (Sect. 5).

2 Background

In Sweden, cities like Göteborg started to grow in the 19th century. At the beginning of the 19th century Göteborg had 13 000 inhabitants which was about doubled around 1850. In 1914, however, the number has grown to over 180 000. The ongoing industrialization and globalization, with Göteborg as the main harbor of Sweden, attracted people from the countryside to the city. Between 1900 and 1915, companies such as AGA

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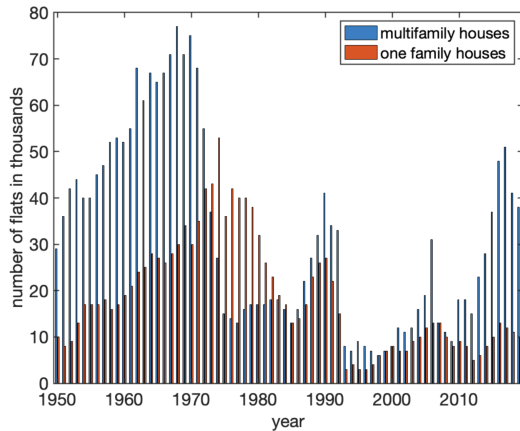


Figure 1. Number of flats built each year in multifamily houses and small one family houses in Sweden based on data from SCB (Statistics Sweden).

(Aktiebolaget Gasaccumulator), SKF (Svenska Kullagerfabriken), ESAB (Elektriska Svetsnings-Aktiebolaget) and VOLVO (registered by SKF, but since 1927 VOLVO) were founded with a need for labour as a consequence. Because of these new establishments, Göteborg started to grow beyond its original borders. Industry, as well as housing for people, could only find adequate space on the outskirts of Göteborg.

1879 the first tram line, a horse-drawn tramway, was opened and successively extended. With its electrification around 1902, the extension of the tram system gained speed. New industry and living areas were placed in the vicinity of the tram stops. This, however, led exact as in many other cities, to a very sparse city structure, which then leads to increasing vehicle traffic. After the second world war the number of passenger cars in Sweden increased rapidly from ca 50 000 to over two million in 1970 and around five million today.

According to [1] the period between 1870 and 1970 comprises the most successful part of Swedish industrialization and growth. On a per capita basis, only the Japanese economy performed equally well as the Swedish economy in this period.

2.1 The Million programme

Rapid economic growth and urbanisation created a shortage of housing. In addition, the standard of many existing housings was low and not considered to be valuable enough to preserve. The need to build new housing dwellings was already a political issue before the second world war. In the late forties the building activities accelerated. Figure 1 shows the number of flats built in the period between 1950 and 2020. Although the expression “million programme” considers a political decision for the period between 1964 and 1974, even before this period a substantial number of flats were built. To build one million new homes in a country with at that time less



Figure 2. Building site 1961, typical multistorey house with prefabricated elements. Archive Applied Acoustics, Chalmers.

than eight million people was an ambitious public housing programme. In addition to the economical challenge the ambition was increased by aiming on building new subareas at high quality with a good range of services including schools, kindergarten, public spaces or libraries, and meeting places for different groups of households. Most of the apartments followed a well described standard concerning size, use of space, furniture etc. A majority were of the standard three-room apartment (two-bedroom apartment) type of 75 m², planned for a Swedish model family of two adults and two children.

Not only the size/layout of the flats was standardized but also the building materials and technologies used. Often, prefabricated slabs were mounted in a very efficient way to multistorey houses. Typical example of a building site although from the sixties is shown in Figure 2.

2.2 The acoustic challenge

Besides standardization, cheaper and lighter building materials were needed to be efficient from an economic perspective. The choice was light-weight concrete slabs for building up single and double walls both as facade walls but also in between flats. This choice then turned out to create serious problems with respect to the acoustic properties of these buildings.

The archive at Chalmers Applied Acoustics contains a substantial number of reports on air-borne and impact sound insulation measurements in these new buildings. Figure 3 is an example measurement contained in one of these reports [2]. It exemplifies two of the main acoustic problems occurring. The negative consequences of the critical frequency around 800 Hz typical for 7 cm light concrete and and acoustic leakage above 1500 Hz due to poor workmanship. The report was written by Tor Kihlman in 1959 at this time a 25-years-old engineer who 10 years later became professor for building acoustics at Chalmers (see Sect. 4).

The problem of the critical frequency in the middle of the relevant frequency range would not surprise anyone today. Cremer’s paper on the theory on “sound insulation

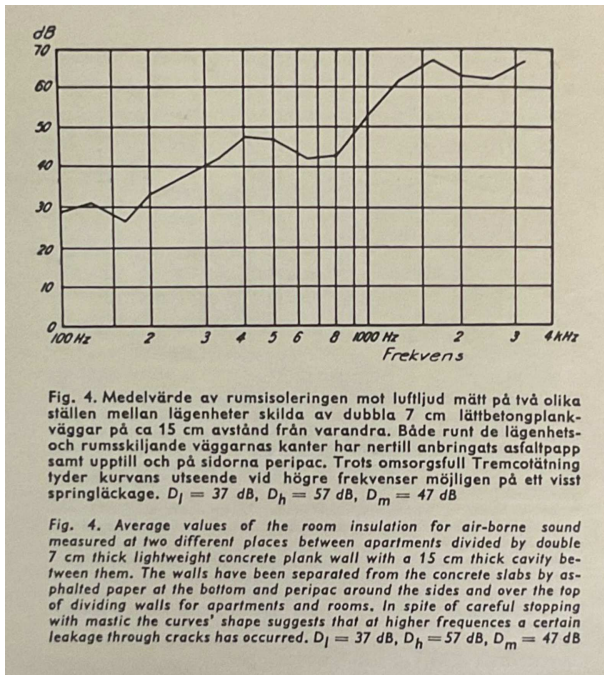


Figure 3. Measurement results of air-borne sound insulation published in [2].

of thin walls with oblique sound incidence” [3] had been published 1942. It might have been a problem of education in building acoustics rather than a lack of knowledge. Of course some areas of acoustics might have been taught in some places as courses or parts of courses. The education of acousticians as a profession, however was not taking place in Sweden at that time.

The various problems with the acoustic performance of the buildings from the fifties and sixties resulted in an increased attention in society for a good acoustic quality of buildings. Consequently Universities like Chalmers for instance considered the education in building acoustics as a chance to attract more students for the civil engineering programme. This was mentioned as one reason in the decision to create a chair in building acoustic (see Sect. 4). The building boom and the associated acoustic problems led to an increase of research and to a growth of consultancies in the field.

2.3 The introduction of objective measurement methods in building acoustics

After fundamental work in acoustics by scientific giants such as Lord Rayleigh and Hermann von Helmholtz the field of acoustics might have been considered by some scientists as complete not offering something new. However, in the beginning of the 20th century the need for further development of acoustics was recognised.

As already described in the previous section, noise was experienced as an environmental problem and it was realised that it is not trivial to design products, houses and environments with appropriate acoustic properties.



Figure 4. Measurement of the influence of the presence of people on the reverberation time [4].

However, at this time there was an additional momentum created by the development in electrical engineering which led over time to the acoustic measurement techniques we know today. At the beginning of the 20th century, there was no satisfactory design of sound sources, pressure sensors or vibration sensors with well defined properties. This was a hinder to carry out systematic research in acoustics. For instance, in 1920 measurements of the reverberation time were still carried out by means of subjective judgment.

Figure 4 shows Vivian L. Chrisler during such a measurement at the national Bureau of Standards in the US. The measurement room shown on the picture was situated in the Riverbank Acoustical Laboratories. In order not to influence the absorption in the room, Chrisler was sitting in a wooden box and only his head was visible. Inside the box he could maneuver the source which originally consisted of tuned organ pipes. After switching off the source he measured the time until the sound pressure was not audible anymore.

A few years later, in 1930 Chrisler and Snyder published a paper on the measurement of sound absorption [5] where they beside others compare this “method of measuring sound absorption by means of the ear” with “methods by which sound absorption can be determined from oscillograph records or by the use of an attenuator box and vacuum tube voltmeter”.

This is just one example of many where electro acoustic devices consisting of microphones, amplifiers and sound level meters replaced the subjective judgment of sound by listening. Activities took place at many institutes such as the Bell Laboratories in New York, Philips Natuurkundig Laboratorium in Eindhoven or the Heinrich Hertz Institut für Schwingungsforschung in Berlin. To establish measurement techniques and use it for research in acoustics supported also the establishment of acoustic laboratories during the thirties and forties around the world. So also at Chalmers as described in the following sections.

3 The start of building acoustics at Chalmers University of Technology

The very first time acoustic was mentioned as part of an education at Chalmers was in a course in the architecture programme in 1885. The course was called “byggnadskonst” which might be translated as “construction art”. The teacher was Bror Viktor Adler, professor at Chalmers, responsible for a number of iconic buildings in Göteborg (e.g. Saluhallen, the market hall). The part of the course was called “acoustic rules” [6]. However there is no documentation from this time.

3.1 The early days

The Chalmers acoustic laboratory was founded 1943/1944 under the lead of Per Brüel. In 1942, while still in Denmark, he had started the company Brüel & Kjær together with Viggo Kjær. Short after that, he emigrated to Sweden. Denmark was occupied by Germany and Per Brüel did not find work in Denmark he liked to do as he said in an interview [7]. In Sweden he first worked for a company where he designed absorbers for their factory halls. Then he got the question from Olof Rydbeck (professor, electronic engineering) and Hjalmar Granholm (professor for building technology) to come to Chalmers to build up an acoustic laboratory. The available laboratory space included two measurement rooms in a shelter in a basement at Chalmers. Later a little anechoic chamber was added for the calibration of microphones.

Much of his time was devoted to developing and building instrumentation for acoustic measurements. During that time a prototype of the famous dynamic level recorder has been developed (see also Sect. 3.2). The Chalmers Acoustic Laboratory under the lead of Per Brüel also carried out various building acoustic field measurements. All the reports from this time are still in the archive of Applied Acoustics at Chalmers.

Two reports from 1946 are especially interesting. The first report describes the measurement techniques used by the Chalmers Acoustic Laboratory for sound pressure, reverberation time, absorption, and airborne and impact sound insulation [8]. As an example, Figure 5 is a schematic of the equipment for measuring reverberation time. The introduction to the report states that it was written for the Swedish Building Research Department as input for the standardization of measurement methods. It is further claimed that the “definitions and description of measurement methods in the report are more comprehensive than the German and American standard proposals”.

Clearly, the intention of the Chalmers Acoustic Laboratory and Per Brüel was to advance acoustic measurement techniques in Sweden beyond the level achieved by the leading acoustic laboratories of that time. This is perhaps not surprising in light of Per Brüel’s later position in the field (see also Sect. 3.2).

The second report describes what could be the first field survey in Sweden concerning peoples’ opinion about the sound insulation in their houses [9]. It is based on

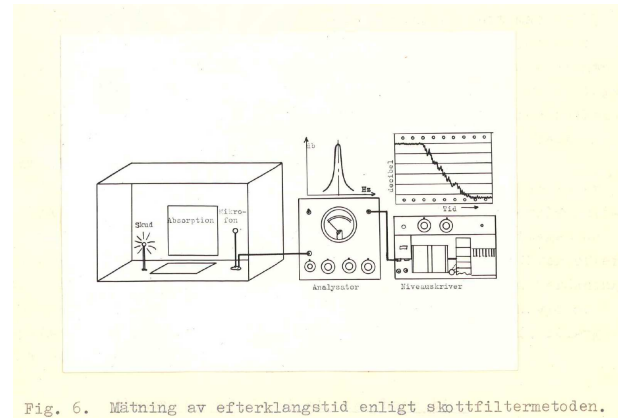


Figure 5. Measurement setup for measuring reverberation time as presented in [8].

a questionnaire which was sent to different households. At the very end Per Brüel however concluded that the number of households investigated might have been too little to obtain reasonable results.

Per Brüel stayed at Chalmers until 1948 at least part time. When Per Brüel started the lab, he got a young assistant, Uno Ingård (in his early twenties) who after the war took over as director of the lab. During this time, Uno Ingård worked on his licentiate degree which he finalized in 1948 [10] under supervision of Olof Rydbeck and supported by Hjalmar Granholm.

With his increasing interest in acoustics but also with his enthusiasm for Phillip Morse who was Professor of Physics at Massachusetts Institute of Technology (MIT), Uno Ingård decided to go to the MIT to obtain a Ph.D. in acoustics, which he at the very end after solving the financial challenges also managed. Before he left, he persuaded his friend Stig Ingemansson to take over the position as director of the Chalmers Acoustic Laboratory. After his Ph.D. supervised by Richard Bolt, who was director of the MIT Acoustics Laboratory, Uno Ingård returned for a two-year period to Sweden to teach acoustics at Chalmers. At that time acoustics had already been part of the education for civil engineers. Uno Ingård probably wrote the very first course material for a course on building acoustics at Chalmers. In 1952 Uno Ingård decided to go back to the MIT [11] where he later became professor of physics and of aeronautics and astronautics while the Chalmers Acoustic Laboratory continued its work under Stig Ingemansson.

3.2 The measurement capabilities at Chalmers Acoustic laboratory

It was very fortunate that the Chalmers Acoustic Laboratory was built up by Per Brüel. Firstly, he was familiar with building up the acoustic laboratory at the Danish Technical University under the lead of Fritz Ingerslev. Secondly, and this might have been even more important, he was a giant when it came to the development of

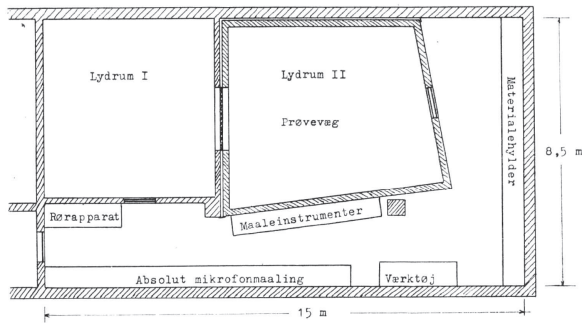


Figure 6. Measurement room for air-borne sound insulation at the Chalmers acoustic lab (from [12]).

acoustic measurement equipment, but also measurement methods. In [12], a description of the acoustic lab, its equipment but also the measurement procedure at that time Chalmers are given. Figure 6 shows a drawing of the lab for sound insulation measurements.

It consisted of a sending room (Lydrum I) and a receiving room (Lydrum II). The receiving room was carefully separated from the sending room by structural decoupling the room from the rest of the building. They decided to have a fixed size of $2 \times 2 \text{ m}^2$ for the measurement opening. Motivation was to be able to build in standardised prefabricated wall elements and by this making the work in the lab more time efficient. In retrospect this decision might not have been wise, having in mind the influence of the partition size on the sound insulation especially around the critical frequency. However, maybe not all aspects with respect to sound insulation of walls with finite size might have been clear at this time.

In front of the transmission suite, there was a place for the Kundt's tube (rørapparat). Per Brüel wrote his Ph.D. on acoustic measurements in the Kundt's tube [13]. Parts of the work certainly were carried out at Chalmers during his time there. There also was a place for microphone calibration. In addition, a working bench and places for material storage and measurement equipment were available.

For the airborne sound insulation measurements the equipment is shown in Figure 7.

Figure 7 shows a tone generator and loudspeaker on the sending side. Microphones and microphone amplifiers are used to measure sound pressure levels. The tone generator created a frequency sweep and the sound pressure levels on the microphones were then recorded on paper on the level recorder which was over a mechanic coupling synchronised with the tone generator.

The level recorder shown in a schematic way in Figure 7 is the famous Brüel & Kjær level recorder 2301 as shown in Figure 8. As mentioned before, the level recorder was developed by Per Brüel during that time. The prototype of the level recorder has been at Chalmers until 1977 when it was given to Per Brüel in connection with the 25 years anniversary of the presentation of Brüel & Kjær in Sweden. Figure 8, however does not show this

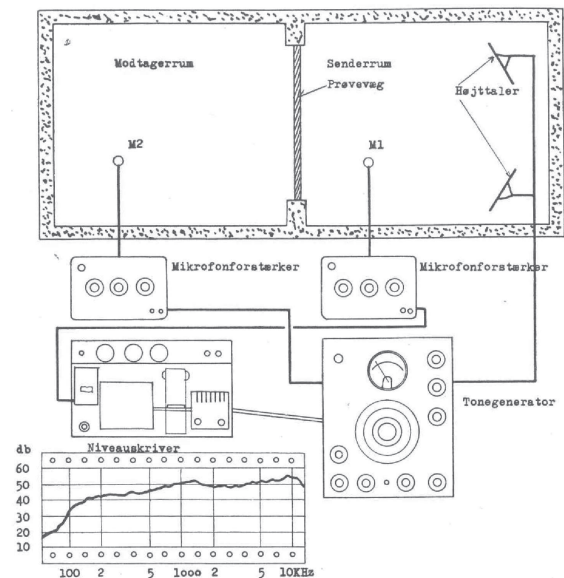


Figure 7. Measurement equipment for air-borne sound insulation measurement presented in [12].



Figure 8. Level recorder Type 2301, source: archive Applied Acoustics.

prototype, but the very early version on the market. In [14] More details to this famous product can be found as well as the statement by Per Brüel, that Brüel & Kjær sold more than 25 000 units of the level recorder.

Most of the today usual building acoustic measurements could also be done in the lab. Exception were impact sound measurements which had to be done in field. For this Per Brüel developed a tapping machine which he presented in [7], see Figure 9. Although the first tapping machine was probably designed by Chrisler and Snyder who published their idea in [15] as early as 1929, Per Brüel, has followed the design he knew from Germany as stated in [14]. It is very likely that he refers to the tapping machine shown in [16] on page 104 which was built at the Institut für Schwingungsforschung an der Technischen Hochschule zu Berlin. The tapping machine in Figure 9 had 5 hammers with a weight of 500 gr each and a tapping frequency of 10 Hz. The fall height was 4 cm and at the bottom of the hammers a slightly convex piece of beech wood was mounted.

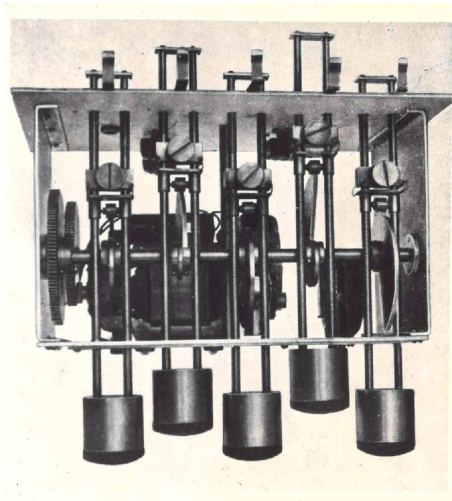


Figure 9. The tapping machine developed at Chalmers Acoustic laboratory [8].

This design is very similar to the tapping machine we know today. Maybe because he later was very engaged in the International Electrotechnical Commission (IEC) which created a standard for this apparatus [14].

One can conclude that the Chalmers Acoustics Laboratory under the lead of Per Brüel was at the forefront of acoustic measurement techniques and that with some modifications the measurement equipment but also the measurement methods in the Chalmers Acoustics Laboratory at that time corresponded to what was used even many years later until digitalisation of equipment took place.

4 The Chalmers acoustic laboratory becoming applied acoustics

The laboratory has since its start in 1943 been a rather independent part of Building Technology at Chalmers. Activities in the fifties and sixties mainly concerned building acoustic measurements due to the expansive phase of the building boom with new building methods and building materials.

4.1 A chair in building acoustics

The poor acoustic performance of some of the new buildings were frequently subject of reports and discussions in the daily press. This might have been a major reason that in 1963 Chalmers decided to create a professor position in building acoustics. However, the position was then announced much broader including not only architectural acoustics but other areas of applied acoustics. The open position was announced 1964, but it took until 1969 when Tor Kihlman (Fig. 10) was appointed as professor by his majesty king Gustaf VI Adolf of Sweden.

In the evaluation committee for the position were beside others Per Brüel and Fritz Ingerslev, at that time already professor for acoustics at the Technical University of Denmark. The delay in filling the position at Chalmers might

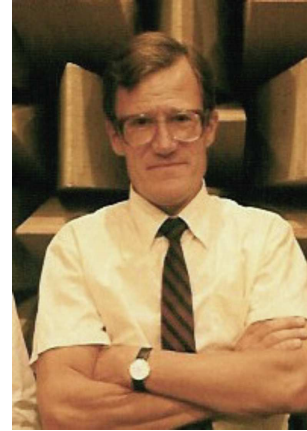


Figure 10. Professor Tor Kihlman in the anechoic chamber of Applied Acoustics.

be explained with the difficulties to find a person with the proper educational profile. During the period between 1963 and 1968 Stig Ingemansson was acting as professor and teaching at Chalmers. However, although Stig Ingemansson was a very good acoustician and teacher, he did not have a Ph.D. When Tor Kihlman finalised his Ph.D. in 1968, he was the very first Ph.D. in building acoustics and probably in acoustics in general in Sweden.

Stig Ingemansson continued with his consultancy company (Ingemanssons Ingenjörbyrå) which he had started in 1956 as a sideline. The company grew quickly to become the largest acoustic consultancy in sound and vibration in Sweden and probably in the whole northern Europe.

With a chair in acoustics the Chalmers Acoustic Laboratory became “Applied Acoustics” as an independent unit. In 1969 Applied Acoustics moved to its own newly built facilities designed by Tor Kihlman. It included besides others an anechoic chamber, a transmission suite, and a reverberation chamber. Although this is not really correct, we often call the year 1969 the official start of Applied Acoustics.

4.2 Epilogue – Applied Acoustics today

Since the start of Applied Acoustics 1969 the activities have grown over time. The original focus on building acoustics has been broaden to areas such as structure-borne sound and room acoustics. Mendel Kleiner started the Chalmers Room Acoustic Group (CRAG) working beside others with at that time ground braking methods for auralisation and different aspects of sound quality. In 1992, Wolfgang Kropp joined Applied Acoustics as young postdoc coming from the Institut für Technische Akustik in Berlin. He became appointed as full professor 1998 as successor of Tor Kihlman. Under his lead the vibroacoustic group added research on rolling noise from tyre/road and wheel/rail interaction to the core research activities of Applied Acoustics. Bigger national and European projects such as Soundscape Support to Health, Hosanna

and Sonorus started an additional line of research with focus on environmental noise in an urban context.

In 2016 Jens Ahrens joined the group as Mendel Kleiner's successor. He started the Audio Technology Research Group at Applied Acoustics working with different aspects of spatial sound such as spatial sound capture and auralization using loudspeaker and microphone arrays.

Today the profile of Applied Acoustics looks very different from the one of the Chalmers Acoustic Laboratory. Building acoustics is just one of several sub-disciplines in acoustics. However, that is not surprising as research is under continuous transformation motivated by the development in society and industry but also in the discipline itself. What will be the future? One of the possible emerging fields might be perception based design. The increasing ability to create virtual environments in a quality allows to carry out experiments in. This will open new doors for research for a better understanding of the complex response of human beings on sound and vibrations in daily life situations.

However, such a transformation also demands different types of laboratories. Applied Acoustics already went a little step in this direction by building "Living Room Lab" (see Fig. 11). The transmission suite once designed for the measurement of air-borne sound insulation has been transformed to a new lab consisting of a living room like furnished room. Behind the window there is a linear loudspeaker array creating the pressure field of simulated outdoor sound environments on the window pane. The lab allows, for instance, for investigating the presence of road traffic on well-being and cognitive performance [17]. The ceiling also contains a loudspeaker array to reproduce sounds from neighbors' footsteps. It allows for simulating and reproducing impact sound on different floor designs (see e.g. [18]).

Finally, over the years, teaching and research education have become an essential part of the core activity at Applied Acoustics. 53 Ph.D. students have finalised their studies since the start of Applied Acoustics 1969 with the majority during the last twenty years. An international two year master programme in sound and vibration has been taught during the last 25 years educating several hundred acousticians who are today working in multitude of different areas with sound and vibration.

5 Final remarks and a brief summary

The million programme was not only a housing programme but had the clear intention to increase the standard of living. The standardized building methods developed during the million programme made it possible to build a high number of flats in a short time. However, this also resulted in that the acoustic problems associated with the building techniques occurred in many buildings. What was intended to increase the standard of living obtained a bad reputation.

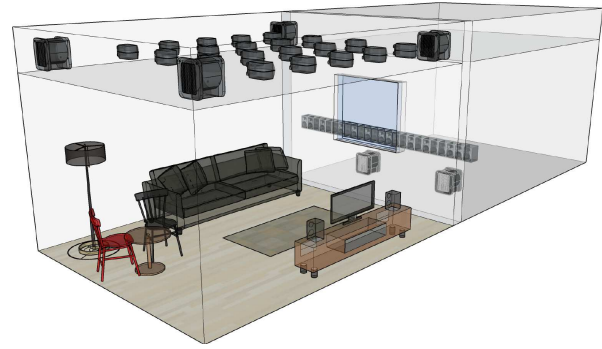


Figure 11. The Living Room Lab at Chalmers University of Technology.

Sometimes this bad reputation was not always deserved as not all buildings produced during this time period were built using e.g. light-weight concrete, but with building technologies leading to high acoustic standards. It is often believed that the acoustic problems were caused by too low requirements in the building legislation at that time. This is however not true; the sound insulation requirements from 1946 in Sweden are essentially equivalent to the current legislation (the main difference is that today's legislation includes frequency bands down to 50 Hz). This means that a building that was built in the fifties and that fulfilled the sound insulation requirements in the 1946 legislation would also pass today's airborne sound insulation requirements. The bad reputation of the million programme buildings is thus mainly connected to the chosen constructions, not to the legislation.

However, as a consequence of the bad reputation, building acoustics became an important issue in Sweden in the fifties and sixties. It coincides with a time in Europe where building acoustics made substantial progress in knowledge and also where talented people with scientific curiosity engaged themselves in the development of building acoustics as a subdiscipline in acoustics. The development in electrical engineering at the end measure sound and vibration accelerated this process.

The start of the acoustics laboratory at Chalmers might look as being based only on a series of lucky incidents. However, on a second glance it is obvious that this would not have happened without people – not necessarily acousticians – who recognized the needs of building acoustics in society and who took the chances offered by history. They asked Per Brüel to come to Chalmers and to build up the acoustic lab when he was in Sweden. They persuaded a talented student named Uno Ingård to get engaged in acoustics although he at the beginning felt that acoustics was not what he wanted to work with. Ingård also found in his friend Stig Ingemansson the perfect person to take over the acoustic laboratory. Finally, the Civil Engineering Department at Chalmers University of Technology at that time understood the value in having a chair in acoustics. That they found with Tor Kihlman an adequate candidate was not self-evident, having in mind that until that time, there had been no one

awarded with a doctoral degree in building acoustics in Sweden.

The activities at Chalmers University of Technology (and at other academic institutions), together with the emerging awareness of acoustics being an important issue for the “normal” person, triggered a high activity of product development during the sixties. Several manufacturers of building materials started their own engineering divisions, and some of them even built their own acoustic laboratories. The curiosity and inventive skills of the engineers working at these labs drove product development, both from a scientific and from an economic point of view. The aspiration to find efficient and simple solutions to the acoustic problems was admirable.

Over the years, the insight for the need of education and research in acoustics varied among those who make decisions in politics or at universities. However, the challenges to create acoustic environments which support health and well-being increased steadily. Almost all product development or large-scale engineering projects in any imaginable context depend on the quality of the acoustic engineering support. Solving practical problems in acoustics requires combining concepts from a variety of disciplines. Developing the holistic understanding necessary to master this demanded and still demand a strong interdisciplinary character of an educational programme – both in its content and in the diversity of students and teachers.

Finally, the authors would like to thank Tor Kihlman, who taught us the importance to fight on all levels for a better acoustic environment in our daily life. This includes not only the education of young students as future sound and vibration specialists, the research with relevance for society, but also influencing politics for the peoples’ best. Without Tor Kihlman, the acoustics at Chalmers but also in Sweden would have never developed to what it is today.

Acknowledgments

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Conflicts of interest

The work behind this paper is funded by internal financial resources and no conflict of interest occurs.

Data availability statement

Data are available on request from the authors.

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