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# ACOUSTICS RESEARCH AT TPD-TNO IN THE 20th CENTURY

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## ABSTRACT

TNO is a leading Dutch organization for Applied Scientific Research ('Toegepast Natuurwetenschappelijk Onderzoek'), founded by Dutch law in 1932. One of its institutes was TPD ('Technisch Physische Dienst'), focused on Technical Physics. Applied acoustics research at TPD started in 1941 in close cooperation with the Technical University in Delft. Initially it mainly covered room and building acoustics, extending in the subsequent years to environmental noise, ship acoustics and machinery noise. The research combined experimental work and modelling, often resulting in contributions to guidelines, legal regulations and (international) standards. The source-transmission-receiver chain was a common starting point, resulting for instance in measurement methods for source description, reciprocal methods for the measurement of transmission and sound transmission prediction models. In close cooperation with other TNO institutes appropriate quantities and allowable levels for noise annoyance were defined. The nature and impact of applied acoustics research will be highlighted, showing some examples from the fields of building acoustics, outdoor sound propagation of road, railway and industrial noise, structure-borne sound source characterization and transmission of ship and machinery noise. Finally, a view is given on the links to current and future research in this context.

**Keywords:** *acoustic research, history, building acoustics, outdoor sound propagation, ship acoustics*

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## 1. INTRODUCTION

Acoustical activities in the Netherlands started around 1930, initiated by prof. Zwikker at the Technical University in Delft, with a focus on noise abatement, building and room acoustics. In 1934 the 'Geluidstichting' (Sound Foundation) was founded, the predecessor of the Acoustical Society of the Netherlands. The activities of that foundation were wider than scientific research, there was a service for measuring and advising and activities to make the general public aware of noise problems. Research and contact with foreign institutes in Germany and the United Kingdom were mainly maintained through the University. In 1932 TNO was established by the Dutch government, the organization for Applied Scientific Research, dealing with a variety of scientific subjects for the benefit of Dutch society. After some discussion it was thought that the practical work of the 'Geluidstichting' would better be placed under the umbrella of TNO, but maintaining the strong link with the University and for that purpose in 1941 the Institute of Applied Physics was founded with the link to TNO and university indicated in the official name: TPD TNO-TU. The institute was also housed in the physical department of the university, as it would be throughout the 20th century. At the start of the institute acoustics was the prime subject while other areas of research at the university, such as heat transfer and optics would become important items too. Another TNO institute was also involved in noise as a health factor and at the start there was close cooperation concerning subjective effects and annoyance.

## 2. ACOUSTICS AT TPD

In the first period the research and development were mainly done at the university while the application - measurements, advice - would be done by TPD. Over the years this partly shifted. The focus was on building acoustics and room acoustics, and therefore the properties of building materials for sound transmission and absorption. Measurement methods needed to be developed, measurement devices created and practical knowledge gained. Plans to develop test buildings for this purpose were hindered by the ongoing war, but could be started soon after the war. Prof. Kosten promoted a lot of the work and TPD assisted in the first ICA congress (1953) with a lot of attention to building acoustics, which was especially needed in the light of the post-war reconstruction efforts in Europe, partly with new construction methods and materials. Later, other acoustic topics also got attention. Increasing traffic caused noise annoyance by aircraft, cars and trains as did growing industrial activity. Furthermore, high sound levels caused health problems at industrial plants and on board ships. In the eighties and nineties, new disciplines were introduced to address future needs: low noise design at the source, active noise control, flow acoustics, acoustic imaging and numerical modelling of sources and sound propagation. Specific models were developed and applied, such as a national method for shooting noise from civil and military training areas, with parts also included in ISO standards [4]. Also models and tools for wheel/rail rolling noise, bridge noise and tyre/road noise were developed. TNO had a key contribution to the development of the PIEK noise programme for reduction of noise from goods delivery, later formalized and adopted in several other countries [5].

As the variety of subjects is rather wide we will further concentrate on three main topics with international impact: Building Acoustics, Ship Acoustics and Outdoor Sound Propagation.

## 3. ACOUSTICS RESEARCH HIGHLIGHTS

### 3.1 Building Acoustics

As said, to characterise materials and buildings, acoustics quantities and appropriate measurement methods and devices had to be developed. The main contributions from the Netherlands came through the university - prof. Kosten - with practical help and assistance from the TPD. This led to internationally agreed methods, standardized in ISO. The low number of the standards indicate the early work on this: ISO 140, measurement methods for sound insulation of materials and buildings; ISO 354: measurement methods for sound absorption of materials and ISO 717: requirements for building performance.

The latter requirements were largely linked to the typical performance of good German buildings, so-called 'soll-curves', both for airborne sound and impact sound. Partly while construction methods were not identical in the Netherlands it was questioned whether these were appropriate. So TPD participated in research by the health institute of TNO about the appropriate requirement for airborne and impact sound insulation. This was conducted along the line of source-transmission-receiver, first of all for airborne sound. To characterise the desired maximum transmission it was questioned what is the dominant source (radio music and speech) and what is an acceptable received level (Noise Rating-curve, more or less equivalent to A-weighting, at background sound level). To describe the source people were asked to choose the best listening level of the radio and that level and spectrum were measured. Quite a job at that time, the octave band filters for instance had to be defined and were produced by TPD, using remnants from American military equipment. The results more or less confirmed the curve in ISO 717 [6].

In the sixties a comparable study was done by TPD for impact sound, since social surveys showed that heavy concrete floors were much better judged than according to the ISO 717 curve. The approach was the same: what is the relevant source (walking) and what is an acceptable level (NR-curve). The typical relevant difference on various floors was deduced from the sound level peaks by human walking and by applying the standardized impact machine [7].

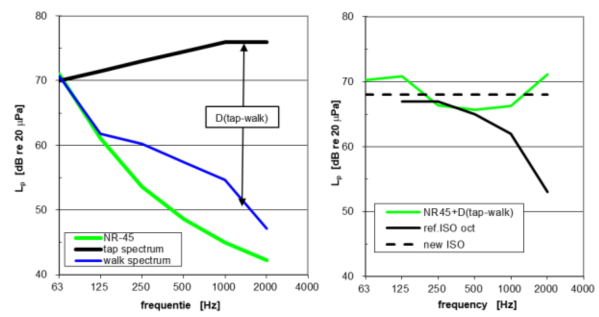


**Figure 1:** Applying the difference in sound level between tapping machine and walking to a concrete floor, thus comparing walking spectrum peaks with NR curve (left) or applying this difference to the NR curve as a direct reference for the tapping machine (right).

That tapping machine was not developed as a representative impact sound, but to provide a load and constant impact sound to facilitate measurements. The result is illustrated for a heavy floor in Fig. 1. For impact sound there clearly is a large difference between this result and the ISO curve. That resulted in changes in the Dutch requirement and only many years later this system was more or less added as an alternative to the ISO standard.

With the requirements fixed it becomes important to realize buildings that fulfil them and to give guidelines to the designers and builders of housing. So in the seventies a lot of attention was given to better understanding the sound transmission between rooms with various building constructions. And it was felt that a transmission model was needed to derive those simplified guidelines. A basis for such models was more or less available, mainly from German literature, but a lot of details were missing to sufficiently describe the direct and flanking transmission, see Fig. 2.

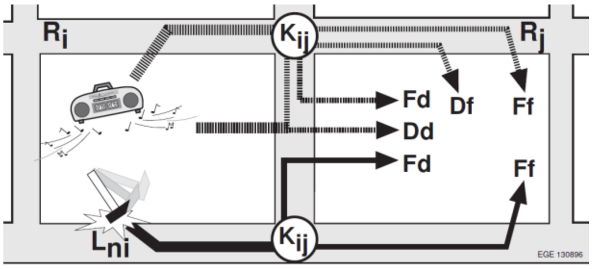


**Figure 2:** Illustrations of the direct and flanking transmission path between two rooms, indicating the relevant describing quantities.

The vibration transmission over the junctions was important ($K_{ij}$) and for heavier building materials the in-situ damping, depending on the construction situation, as characterised by the structural reverberation time. Measurement methods were developed to determine those quantities and data gathered in various buildings [8]. The transmission model derived from these results was used to create guidelines for builders.
The increased attention to road, rail and aircraft noise also made it necessary to consider the sound transmission through facades and the increased number of equipment and installations in buildings. Prediction models for these items were also developed. And for the equipment noise good use could be made of the knowledge gained at TPD for mounting and describing structure-borne sources in ships (see3.2).
In the 1990s a new EU regulation for products and materials actually required a link between the properties of building material and buildings. So some buildings acoustics transmission models needed to be standardized and these results formed an important input to the new European standards EN 12354, part 1 (airborne sound ), 2 (impact sound), part 3 (facade) and part 5 (installations) [9]. Some parts of these standards later became ISO standards, indicating a wider need and use than Europe.

### 3.2 Ship Acoustics

The propellers and engines of ships are strong sources of sound and vibration and the steel ship structure facilitates transmission to the cabins and into the surrounding water. The latter is of course of prime importance for naval ships, but in general also for underwater life as became clear later. To tackle these problems TPD started around 1950 with a lot of measurements aboard ships to gather data. Combined with the available general knowledge at the university about vibrations, scale model rules and properties of rubber, this allowed fruitful developments of less noisy sources (propeller, gears) and better resilient mountings for engines.
In the 1970s this new knowledge led to prediction models for the sound and vibration transmission in ship structures. It also led to the development of dedicated laboratory setups for detailed research such as a test bench for resilient mountings, and a reverberant water basin that was constructed as an inside-out ship to test and improve different solutions for resilient mounting and constructions (see Fig. 3). Although much of the research was done for the Dutch navy, the spin-off was beneficial for the consultancy work for commercial shipyards, varying from seagoing ships to the Rhine barges. As pioneers in ship acoustics, TPD organised two international symposia on ship acoustics [10].

Two specific research tools were developed and used in this area, namely the application of reciprocity in measurement [11],[12] and scale models to study structure-borne sound transmission and exhaust noise systems and silencers. Reciprocity allows us to measure the velocity of the ship structure due to a sound source elsewhere instead of measuring sound pressure at that point due to forces excited on the structure at several points; see Fig. 4.

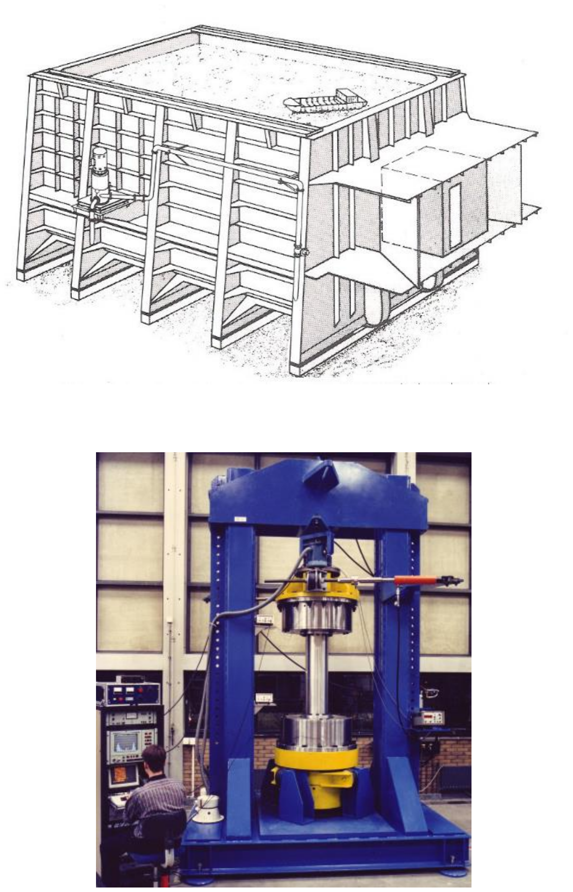

**Figure 3:** Top: Reverberant water tank as inside-out ship and bottom: test bench for resilient mountings with appropriate preloading.

For structure-borne sound this is especially beneficial since the excitation has 6 degrees of freedom (force and moments in and around x, y, z-axes) compared to the 1 degree in airborne sound transmission. Furthermore, there is the practical advantage, both in airborne and structure-borne sound transmission that microphones and accelerometers are much smaller and easier to mount in a complex source environment than big loudspeakers and exciters.

A specific example of reciprocal experiments is the case were the sound source cannot be decoupled, such as a cavitating propeller. Still then, the source strength can be determined by considering also the sound source in the reciprocal experiment as a reciprocal element using it as a microphone in the direct experiment by measuring the open voltage of the loudspeaker.

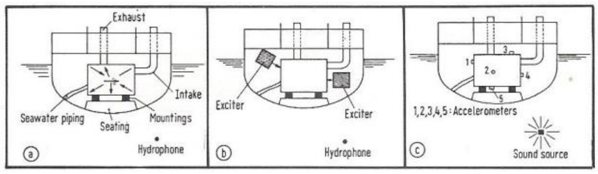


**Figure 4**: Options to measure sound transmission through a ship's hull into water: (a) measuring path transmission is hardly possible, since decoupling of paths is not possible in working condition, (b) exciting at sources is often practically difficult and what is the appropriate source position, (c) accelerometers are easily mounted in all positions and for all measuring directions.

Another important aspect is the adequate description of structure-borne sound sources. Airborne sound sources can normally be described independent of the surrounding, by sound power and directivity for instance, but for structure-borne sound sources with multi degrees of freedom and coupled to the surrounding structure that’s not so evident. Much work has been done to find practical and sufficiently reliable descriptions, varying from equivalent forces to modelling with blocked forces and internal impedances. This work also resulted in a number of international measurement standards which are not only applicable to shipboard equipment but to equipment in general.

Towards the end of the century, the experimental work was more and more supported by development of calculation models [13] that led to a better understanding of the underlying mechanisms and showed to be sufficiently accurate and of course easier to apply.
The knowledge partly developed in ship acoustics was also put to use more broadly. Low noise design of machinery and equipment was taken up in the eighties and applied to products varying from MRI scanners to automotive and railway components and bridges. The combination of empirical and modelling techniques, including scale modelling, provided a strong knowledge base, available to TNO’s clients.

### 3.3 Outdoor sound propagation

While the attention after the second world war was on reconstruction and thus on building acoustics, the growing mobility and industrialization led more and more to noise nuisance due to road traffic, air traffic, rail traffic, shipping and industrial activities. So as to reduce

the received levels the sources can be made quieter or the transmission of sound can be reduced. TPD could contribute to this mainly for those sources that were also produced or created in the Netherlands - ships, industrial sites, city buses - but hardly for the others. For cars, mopeds and motocross bikes, noise limits were set following a standardized measurement method (type approval or in-situ checks). But often those measurement procedures were not representative for the normal driving conditions. Various studies have been conducted to improve and change those measurement procedures to make them more appropriate. For example, the noise of a stationary running moped is not at all representative, but accelerating at stand still improves this a lot.
To predict the sound level of roads and railways at distance, those source data for cars and trains are not directly useful and sufficient. We need the sound production of traffic flows including the interaction between the cars and the road surface or the train wheels and the rails. In the 1970s large measurement campaigns were conducted to this end and in the nineties the mentioned interaction between vehicle and track was studied in detail, leading to source models for trains (TWINS [14]) and for cars (TRIAS), including the effect of absorbing road surfaces.
The sound propagation from roads, railways and industrial sites is influenced by many factors, but in the early days the influence of the terrain, obstacles and more importantly weather conditions were only partly known. Some available propagation models were empirical models based on dB(A)-measurements and thereby not applicable to other sources. In the 80ties a law on noise annoyance was in preparation that triggered much research to enable accurate predictions of sound levels at distance from industry, roads and rail tracks. Outdoor sound propagation was one of the main points of study in general, deriving where necessary source specific adaptations later. As for many engineering approaches, dealing with octave bands was, and is, considered to be sufficiently general.
To study the influence of weather conditions long-term measurements were performed at distances from a busy nearby highway, acting reasonably as a constant line source, while monitoring the weather conditions. From these measurements it was concluded, among others, that reproducible measurements are only possible within certain favorable weather conditions and the year-average sound level could be deduced from that by applying some statistical adjustments. So the same approach was chosen for prediction methods: calculate for weather conditions that are favorable for the sound transmission, like down-wind, and apply adjustments to get for instance the year average level. This has of course consequences for the effects of the terrain -soft or hard ground- , screens and objects. And those effects were studied theoretically, with scale models and outdoor measurement campaigns, thus strengthening each other [15].

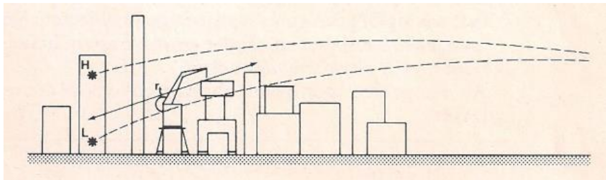


**Figure 5:** Curved sound ray through industrial installation to determine additional attenuation.

To study the effect of combinations of hard reflecting ground and soft ground, measurements were done in Friesland, a part of the Netherlands with a lot of lakes between grassland. So all kinds of situations could easily be studied there. The resulting propagation model in its most general form was applicable to industry [16] while for road and railway dedicated models were deduced from this. This propagation model was largely adopted also by Scandinavian countries and was a starting point for international standardization at the end of the 20th century [17]. An aspect that had to be incorporated there was the effect of uneven terrain, a neglected aspect in the Netherlands, being as flat as it is.

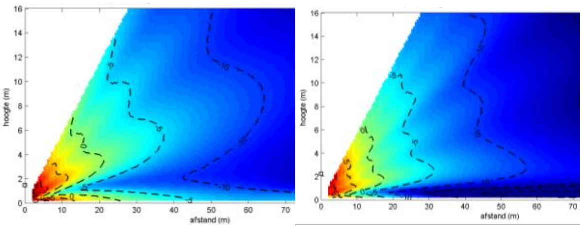

**Figure 6:** Calculated excess attenuation over hard ground (left) and grassland (right) at 500 Hz under downwind conditions.

## 4. CURRENT DEVELOPMENTS AND OUTLOOK

Since the turn of the century, acoustics has continued as a key topic at TNO. Today, the main acoustics department at TNO is Acoustics and Sonar, based in The Hague. It is active in the fields of underwater acoustics, environmental noise and ultrasound technology. Environmental noise has continued relevance due to traffic growth, new infrastructure and more dwellings near roads, railways and airports. Work continues on noise control, propagation and source modelling, experimental methods, standardization and the link with national and EU legislation. TNO was involved in many European research projects including Harmonoise/Imagine, Metarail, STAIRRS, Acoutrain, Roll2Rail, Transit, all relevant for standardization, for example on railway noise source terms [18]. The current EU project LENS is focusing on quieter motorcycles and light vehicles. Also, policy support studies for the European Commission have been performed, including noise source legislation for outdoor machinery [19], and noise policy and impact studies for road vehicles and railways [20]. Underwater sound is a major field of activity, including naval research, sonar technology, and environmental effects of shipping and wind park construction on sea life.

Applied acoustics remains a topic for the future at TNO due to its societal impact, complexity and innovation potential, requiring specific experience and expertise and international cooperation.

## 5. ACKNOWLEDGMENTS

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