Of Acoustics and Instruments*

Memoirs of a Danish Pioneer – Part 1

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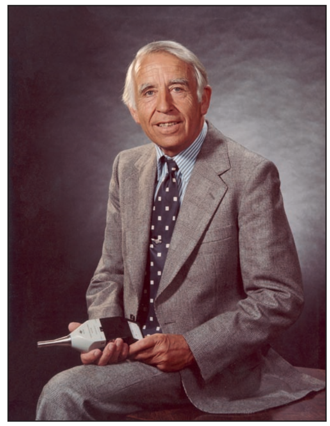
Dr. Per Vilhelm Brüel was born in Copenhagen in 1915. He went to school in Åbenrå (South Jutland), Denmark where half of the population was German. Hence, he became bilingual in Danish and German at an early age. Today, he is fluent in Danish, German, English, Swedish and a little French and Italian. He studied physics and electronics at the Technical University in Copenhagen. Brüel finished his studies in 1938 and received a Master of Science degree. During his long and productive career he was awarded honorary doctoral degrees by the Universities of Copenhagen, Gothenburg, Bologna, Dresden, Shenyang, Prague, Tongi and Krakow.



Brüel's collaboration with Dr. Viggo Kjær began in 1941. The two men formed an excellent team. In 40 years, Brüel & Kjær grew from nothing to a large and economically secure company with annual sales of $150,000,000 and 3200 employees worldwide. Per Brüel was in charge of sales and all new developments in acoustics. He traveled all over the world, gave lectures on technical matters, arranged seminars for B&K sales people and major customers, authored over 100 articles, and actively participated in acoustics conferences. Viggo Kjær stayed closer to home and dealt with production, administration, personnel and financial matters. Dr. Kjær came to the partnership with an electronic instrument development background, having produced vacuum tube voltmeters and component quality control test bridges.

Dr. Brüel has held a number of special assignments. He was a member of the Council to the Danish National Bank, a Member of the Board of Appeal for the Danish Environment Tribunal and Vice President of the Federation Aeronautique in Paris. His many honors include: the Lord Rayleigh Gold Medal (London); Member of the National Academy of Engineering (USA); Tissandier Diplome (Paris); Silver Medals from the Audio Engineering Society (USA), Acoustical Society of America (USA), and the Danish Design Guild.

Per Brüel holds eighteen patents on acoustical instruments and two on acoustic absorbers. His pending applications to the Danish Patent Office include: a precision sound source, a transmitter for measuring the speech transmission index, a piston-phone calibrator, an electrodynamic tapping machine for measurement of impact noise isolation and a vertical standing wave tube.

Dr. Brüel has utilized almost every modern mode of transportation during his many years of travel throughout the world including motorcycles, automobiles and private aircraft. However, flying became his life's passion. He accumulated 8,760 hours as pilot-in-command holding glider, single-engine, multi-engine (up to 18,000 lbs), instrument and aerobatic pilot ratings.

This is Part 1 of a two-part series of articles. Part 2 will be published in a subsequent issue of Sound and Vibration.

I was asked to write about what happened in the field of acoustics before the Danish Acoustical Society was founded in 1954. I did that willingly for many reasons. I think it was good that the Society utilized its 50th Anniversary to present an overview of the times before and after its foundation. I have taken this opportunity to mention some individuals and their contributions, which I fear might sink into oblivion. I will also briefly illustrate some technical results, that could be useful and that may not otherwise be published. My narration will not be in chronological order and, as there are several points missing, my paragraphs should be treated as episodes. In particular, I wanted to write about Professor P. O. Pedersen's contributions and events following the Second World War. P. O. Pedersen is a key figure in Danish Acoustics. He took the initiative to start the "Lydteknisk Laboratorium" (Sound Technology Laboratory) at "Den Polyteknisk Lærenstalt" (The Danish Technical University – DTU), and the "Lydteknisk Institut" (Sound Technology Institute). This only touches on P. O. Pedersen's work as he fostered a horde of ideas in many fields including physics, electro-techniques and civil engineering and even published a book on the national economy. All this can be found elsewhere, so only the field of acoustics will be dealt with here.

P. O. Pedersen came into my life in 1929 at 14 years of age when he gave me a thick book *Teknikkens Vidunderland* (Wonderland of Technology) edited by Vilhelm Marstrand. In that book P. O. Pedersen had written a chapter on radio and electro-magnetic waves. In those days I had some disputes with my family, as they wanted me to be a forester, that was the family profession. I was interested in electronics, physics and conventional engineering. If I absolutely insisted on becoming an engineer then my work should deal with building bridges, roads and railways and definitely not with radio and electronics, which was not remunerative at the time. P. O. Pedersen's article came to my rescue by influencing my parents. So I became an apprentice to a blacksmith rather than to a forester. My next contact with P. O. Pedersen was when he became my teacher at the Technical University. After that, apart from interruption for military service, I was his assistant until his death. I have naturally only reported on situations where I have been directly involved.

P. O. Pedersen, Dr. Phil.

There are two publications concerning the work carried out at the Laboratory. The first is by P. O. Pedersen: "Lydteknisk Undersøgelser I årene 1935-40 I Den Polytekniske Læreanstalts Laboratorium for Telegrafi og Telefoni. Ingeniørvidenskabelige Skrifter 1940, Nr. 5" (Investigations in Sound Technology during 1935-40 at the Danish Technical University Laboratory for Telegraphy and Telephony. Engineering Science Papers, 1940, No. 5). I wrote the complete text and all the drawings and photos up to page 50. After that, P. O. Pedersen wrote the Addendum pages 51-76. It was quite natural in those days that P. O. Pedersen was the sole author, as it was he who was the man in charge and therefore responsible for the laboratory. The second publication which I would recommend is a continuation; however, with two authors, namely Fritz Ingerslev and A. Kjerbye

*This article is based on "Episoder og Resultater inden for Akustikken för 1954" (Episodes and Achievements in Acoustics before 1954) by Dr. Techn. Per V. Brüel. Translated from the original Danish by Harry K. Zaveri. It was originally prepared by Dr. Brüel for presentation at the 50th Anniversary of the Danish Acoustical Society in 2003.

The "Right Stuff" for Electronics in 1941

Per Brüel and Viggo Kjær decided to join forces to build a new acoustic instrumentation business in the middle of the largest war ever to rage over this planet. They chose to venture in electronics (an industry in its youth) and pioneer in acoustics (an area of physics fraught with mystery in 1941 and still less than fully understood in 2008). Suffice to say, they were brave fellows. Since they succeeded beyond all reasonable expectations, we may conclude they exhibited brilliant foresight.

Note that Brüel & Kjær was founded only two years after the Hewlett-Packard Company was formed in (then war-free) California. While it predated such measurement giants as Tektronix (1946) and John Fluke Company (1948), it was preceded by an important American social experiment, the General Radio Company (1915), which competed directly with Brüel & Kjær in a number of product lines.

The evolution of a single device dominated the electronics industry for the first 60 years of the 20th Century. Advances in measurement instrumentation directly tracked the evolution of this single component. That device was the *vacuum tube* or "thermionic valve" that grew from technical observations of Thomas Edison as he pursued and refined the incandescent electric lamp. The 'tube' became the heart of radio, birthed radar and sonar, paved the way for television and gave us the ability to perform precise (transduced) measurement of all manner of physical phenomena.

In 1904, John Ambrose Flemming gave us the 'valve' that bears his name. This device was a two-element vacuum tube, a 'diode' implemented by sealing an electrically-heated *filament* cathode and an anode *plate* within a (tube-shaped) glass envelope and terminating the connections to these elements through pins at the base of the tube. *Flemming's valve* was useful as a rectifier, and more importantly as an element in a radio-frequency detector. Flemming's valve was far more efficient at this task than was a (mechanically taped) 'coherer' formed of metal filings in a glass tube.

In 1906 Lee de Forest patented a three-element tube or 'triode.' He added a central *control grid* and called his device the *Audion*. In 1911 he demonstrated that the Audion was an ideal amplifier. Small voltage deviations at the grid could produce far-larger proportional swings at the plate. Shortly thereafter, the Audion was used to construct an 'oscillator' or sine-wave generator. Electronic amplifiers and oscillators gave immediate rise to all manner of analog computational circuits and electronic instrumentation became immediately feasible; several exciting industries were birthed. The General Electric Company spawned RCA in 1919; in 1921 RCA initiated the commercial production of electron tubes.

The triode evolved over the years, but demonstrated a fundamental frailty when used for high-frequency applications: it would break into unwanted oscillation when used in circuits focused upon a few hundred kHz. This was eventually identified as being caused by grid-to-cathode capacitance. The problem was solved in 1926 by adding a fourth-element, a *screen* (second grid), making the improved tube a 'tetrode.'

Tetrodes (like triodes) still had some performance issues. In particular, the performance characteristics suffered undesirable abrupt discontinuities. This was solved in 1929 by adding a fifth element, a *suppressor* grid, to form the functionally superior 'pentode' tube. The fundamental structure of the pentode led electronics technology through the 1960s, even after the 1948 invention of the 'transistor' that would eventually replace tubes with solid-state components of ever increasing internal complexity, ever shrinking package envelopes and ever improving energy efficiency.

Somewhere within the 1920s, another important vacuum tube breakthrough was made. It was recognized that the cathode did not need to be the filament. Instead, an *isolated cathode* could be heated by a separate filament. This seemingly small change in tube topology had an enormous effect upon circuit design. It meant that the tube's cathode could be heated using the alternating current (AC) available as the line or 'mains' power, while the isolated cathode was held at a required DC potential. In essence, this eliminated the need for batteries or DC supply to power the cathode heaters, simplifying circuits and reducing instrument weight and cost.

Tube performance also improved when higher vacuums were drawn on the glass enclosures. Early tubes had only modest or 'soft' vacuums drawn during manufacture. In some cases, small quantities of other gases were introduced, under the mistaken assumption that this was actually required for the tube to operate. Tubes improved by "sucking harder" were termed *hard* tubes and they worked better than those with any gas within the envelope. This 'hardening' led the way to simplify bottle and pin manufacture, eventually leading to *miniature* and *subminiature* tubes with simple wire pins penetrating the glass envelope. This format eliminated the prior brass and/or plastic bases and machined pins.

In 1941, the methods of designing, prototyping and manufacturing electronic devices were very different from today's. While today's instrument designer may be satisfied to simulate his circuit mathematically prior to approving the layout of a multilayer printed circuit board housing surface-mount components and may be willing to have his computer-generated artwork fabricated for a lead production run, 1941's designer knew the value, nay felt the necessity, of fabricating and debugging a prototype circuit *breadboard*.

In today's parlance, a breadboard is a temporarily fabricated circuit built on a plastic block housing hundreds of (common-wired) rows of wire or pin grasping sockets. Such prototyping boards are designed to accommodate modern *standardized package* components such as integrated circuits, resistors, capacitors, diodes, etc. In 1941 the prototype was literally constructed on a wide plank, probably one liberated from the kitchen. Large components, tube sockets, controls and strips of *solder links* were nailed down to the breadboard. The leads of the remaining components were soldered between the lugs of the firmly mounted components.

This actually modeled the manner in which a product would be assembled. Commercial instruments (as radios) were structured upon a metal *chassis*, a carefully designed, folded, welded and punched box-like metallic structure. Tube sockets, transformers, stack rectifiers, lamps, switches and other controls were all mounted to this and the remaining components soldered between the resulting tabs. Production drawings always included a *schematic* and a *pictorial layout*. Obviously, control placement often favored simple assembly over obvious and simple operation. This meant clear operating manuals were important.

Testing of an assembly was similarly time consuming. The only effective way to 'delouse' bad assemblies was to use a testing technician who understood the circuit at the design level. Since components were scarce, on-the-fly substitutions were the order of the day and an assembly could not be scrapped. Successful quality assurance in 1941 meant every purchased component left the assembly area in a fully functioning product.

Nielsen, "Lydteknisk Laboratoriums Arbejde 1941-46" and also "Ingeniørvidenskabelige Skrifter 1947, Nr. 2."

Environmental Noise Guidelines

One might say that overall our environmental noise laws are adequate and function satisfactorily in several countries. Over the years I have been involved in formulating and approving noise regulations in Denmark. There are numerical limits, a few measurement methods and some details I wish were different. However, we can draw comfort from the fact that minor mistakes we make in the field of noise control can be repaired. We can reformulate the laws at anytime, if we find them to be harmful, unnecessarily costly or in any other way inappropriate. We do not do irreparable damage such as that caused by pollution of subsoil water, felling of trees or CO2 emissions. Therefore, we can fortunately emphasize the 'guiding' expression and permit variations in many situations without causing irreparable damage.

I wish that journalists and politicians who comment on noise, would not make references to dB alone, but endeavor to use dB(A), dB(C), dB(peak), so we know what is meant. We would also like to know if it is the average or the maximum value, if they are measured with 'Slow' or 'Fast' weighting or with time constant $\tau < 50$ µsec for peak values. I will readily admit that if a politician or an architect could talk about noise matters that they fully comprehend, they would not have much to say.

Miljøankenævnet (Environmental Appeal Agency)

As members of the Danish Environmental Appeal Agency, engineer Jørgen Petersen and I have been advisors for noise matters. We have had a number of exciting projects. They included huge million Kroner cases such as Kastrup Airport in Copenhagen and 'Enstedværket' (power station) near Aabenraa. In contrast, the nighttime of a priest in Fyn was disturbed by his neighbor's weathercock when the wind varied in direction. The measured noise was lower than the legally permitted levels. Despite this, the priest took the case right to the top through the municipality, the state and finally to the Environmental Appeal Agency. A commission of four was sent to Odense to survey the site. After spending thousands of dollars of public funds, the case was ended when I borrowed a ladder and a small oil can. Two or three drops of oil brought both the weathercock and the priest to silence.

Enstedværket, which is close to Aabenraa fjord's very deep waters, is a modern, effective and a clean running power station, which supplies most of the electricity from Frederikshavn to Altona. Every effort has been made to ensure that the power station does not pollute, smell or disturb. Nevertheless, the power station emits a low very deep hum, the noise level of which is a few dB over the permitted nighttime levels. Using rational arguments where the Environmental Appeal Agency played a vital role, we avoided demolishing the power station by permitting the existing noise emissions.

One can learn from these two examples: 1) noise limits, though they are guidelines, in the hands of bureaucrats can be very costly to society; 2) an environmental appeal agency can find a solution that is both economical and humane; 3) environmental agencies at lower levels should also suggest practical solutions, so that insignificant cases do not end up costing millions. Instead of fixed limits, common sense should rule. I have seen Chinese sleep soundly beside a noisy diesel engine. On the other hand, I have seen a man have a nervous breakdown from the weak sound of a gunshot at a distance. He had experienced horrible years in a German concentration camp. We now have a set of noise guidelines in Denmark which we cannot abolish simply because we do not have others to replace them. We should, however, organize them so that we get the same guiding limits as in the European Union. It should be pointed out that significant differences both higher and lower are rather common. One should not be allowed to shut down an airport, demolish a power station or avoid laying down a railway track, just on the basis of noise limits. Noise limits depend on individual circumstances. In both the above cases, the guiding noise limits were directly misleading.

Pedersen and the Sound Technology Laboratory

Danish Acoustics owes much to Professor P. O. Pedersen. I will not be reporting on P. O. Pedersen's career as the Dean of the Danish Technical University; I will stick to his acoustics contributions and not provide details on the 'Poulsen Arc' or 'Telegraphone' which he developed together with Valdemar Poulsen. One could say, however, that both the Poulsen Arc and Telegraphone have something to do with acoustics. The first words that were reproduced through an electro-magnetic medium were made using the Telegraphone. If one wishes to learn more about P. O. Pedersen, I would refer to "Miscellaneous Papers" published in a series by Ingeniørvidenskabelige Skrifter, B nr. 12, 1934, as a set of P. O. Pedersen's articles. At the back of this publication there is a list of over 97 articles which P. O. Pedersen authored up to 1933. His

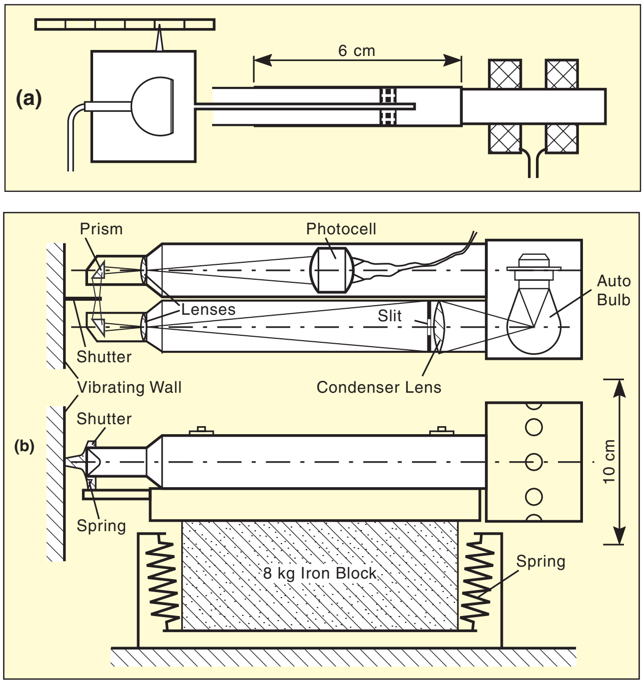


Figure 1. (a) Standing wave tube. (b) An optical instrument for measuring the vibration of a wall.

interest in acoustics came about due to a tragic event.

The Danish Broadcasting Service in 1932 wanted its own premises (Stærekassen). Technical responsibility was under the Post and Telegraph (P&T) service, which also involved acoustics. Architect Jacobsen had found an Austrian immigrant Oelsen, who was employed as a consultant for acoustics issues. He asserted that, in order to achieve a good acoustical environment in a room, lead panels should be built into the outer walls. Oelsen must have been very convincing as architect Jacobsen hired him as a consultant against P&T's wishes. Oelsen was also a consultant to Grundtvigs Kirke (Grundtvigs church) in Copenhagen. That such a situation could exist 45 years after Lord Rayleigh, 35 years after Sabine and 10 years after Vern Knudsen, when all the fundamentals were presented in simple language, is incomprehensible to me. But P&T went along with his recommendations and the finished building was a disaster. The Broadcasting Service would not use these premises and there was a huge scandal. The chief architect got away with it, while the blame was passed on to P&T. Their chief engineer, who was a good acquaintance of P. O. Pedersen, was highly depressed over the problems, became terminally ill and died shortly thereafter.

P. O. Pedersen took his demise rather personally and decided that the Laboratory for Telephony and Telegraphy (LTT) should gather knowledge about acoustics. Vilhelm Jordan, who was an experienced electrical engineer, headed the new department. He had recently spent a few months in Berlin with Erwin Meyer at the Heinrich Hertz Institute and had learned a lot about sound. Jordan was clever and quickly started working on the problems. He constructed several models of a standing wave tube for measuring the sound absorption of acoustical materials and an instrument for measuring the vibration of a wall section (see Figures 1 and 2). A 1/10th scale model of the town hall ballroom was built and measured acoustically. One could now compare the model with the actual room. For this measurement, a large Telegraphone was built using a flat steel wire. This recording device was used to change the frequency accordingly to scale. One could record both speech and music on the recorder and replay it at ten times the speed in the model. This scale modeling technology was quite unique in 1936.

In 1938 P. O. Pedersen founded the Akademiet for De Tekniske Videnskaber (ATV), (The Academy for the Technical Sciences) and LTT's Sound Technology Department became the Sound Technology Laboratory under ATV along with others, e.g. 'Svejsecentralen' (Welding Center). The Svejsecentralen used ultrasound to control

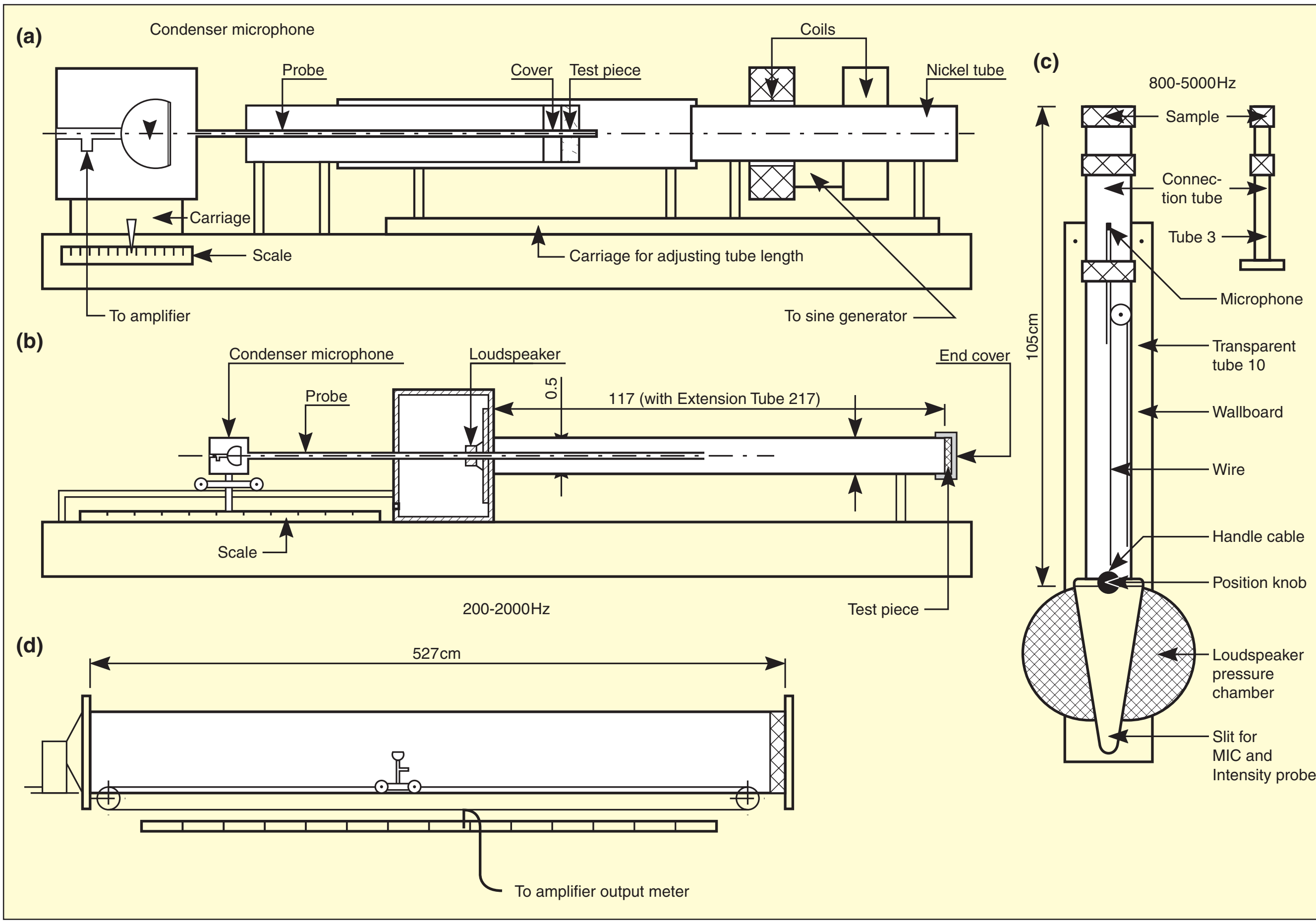


Figure 2. (a) Standing wave tube (SWT) for measuring acoustic impedance at high frequencies, made at LTT around 1930. (b) Later model was in production at B&K for more than 40 years. (c) Newer vertical SWT covering frequency range 100 Hz to 5 kHz with two tube diameters: 10 cm and 3 cm and movable 6-mm microphone. (d) Older LTT tube developed by V. Jordan.

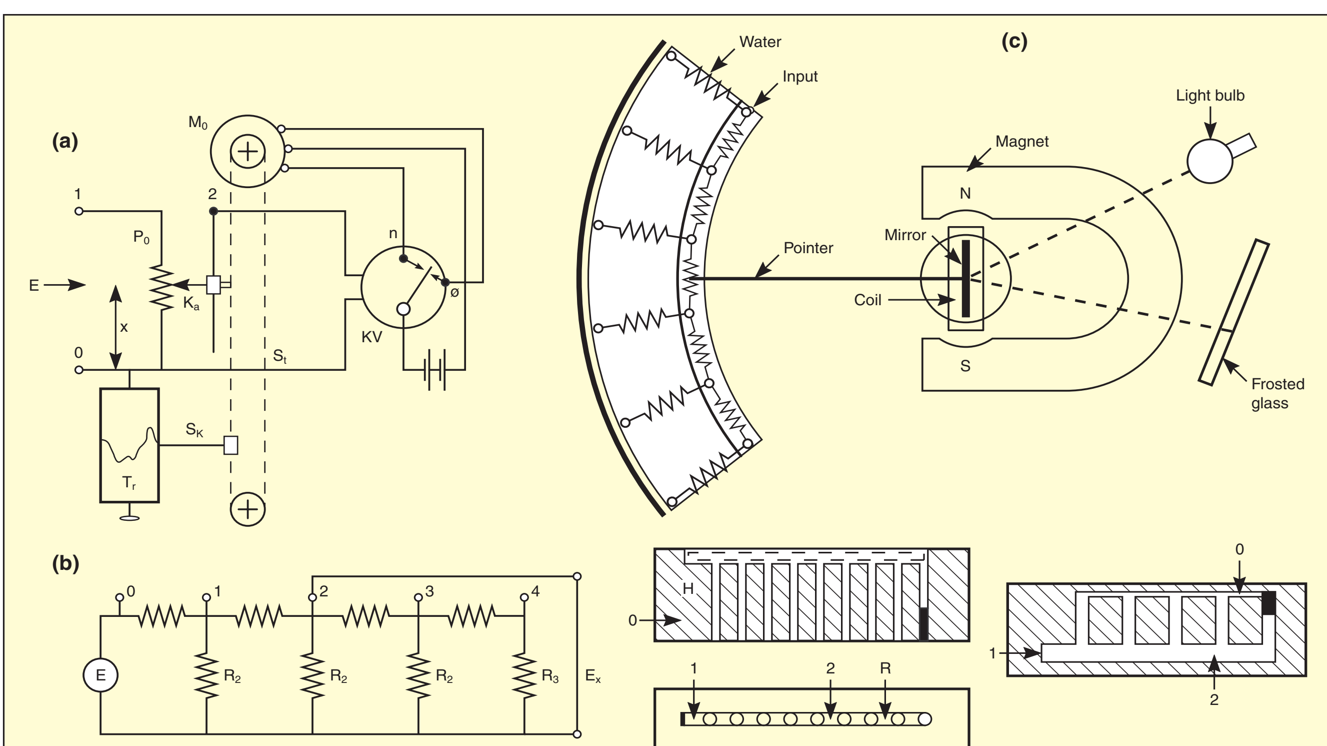


Figure 3. Jens Oskar Nielsen's logarithmic potentiometer is a chain of T-link resistors, where the resistive medium is water. (a) Principle of the writing logarithmic potentiometer. (b) Some of Nielsen's original drawings. (c) Practical construction of level recorder, with a moving coil element, and pointer tip that dips into the water potentiometer. Total dynamic range can be changed by changing the water level,

welding operations and later developed the first ultrasonic instruments for medical diagnostic tests on humans.

The World's Fastest Level Recorder

The world's fastest level recorder was developed by J. Oskar

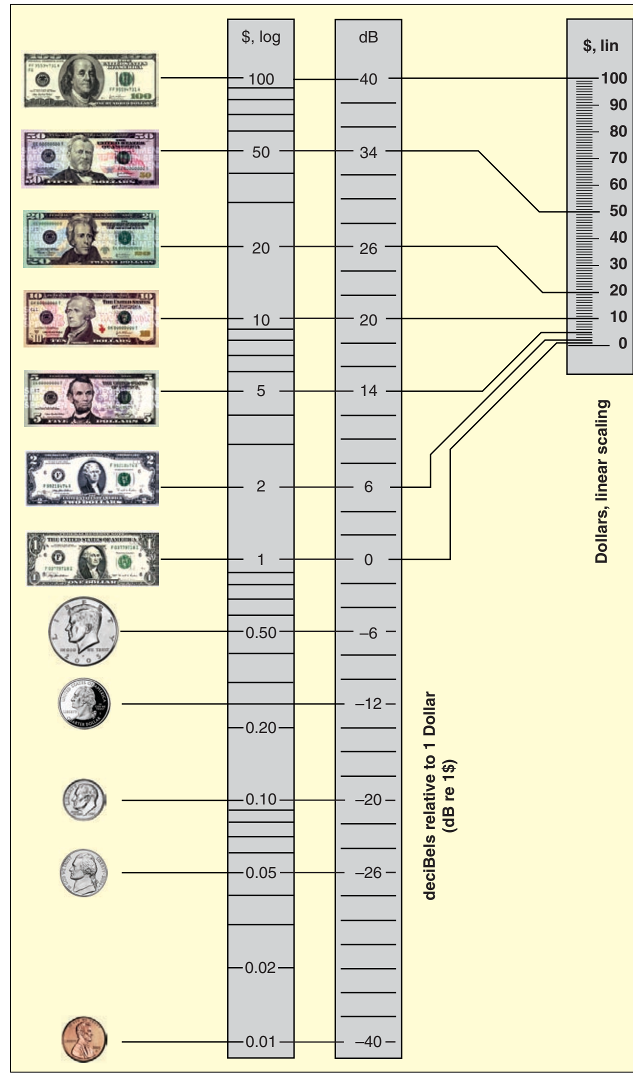
What's a Level Recorder?

Before answering the question of WHAT, we must answer the question of WHY. One answer lies in the unbelievable span of noise levels encountered on a daily basis. The temperature gage on your car, the thermostat on your furnace and your oven temperature range are but pinpoints on a common voltmeter scale. But in acoustical measurements, we deal with very wide measuring ranges.

First of all, we are often dealing with the human ear which has a hearing range from the threshold of hearing (termed 0 dB sound pressure level) up to the threshold of pain (termed 140 dB sound pressure level). Forget the mathematical explanation. If the threshold of hearing were 1 on a linear scale, the threshold of pain would be 10,000,000. Isn't that an astounding wonder of nature? It is not unusual for your city or your factory engineer to be interested in a span of 1:1000. That is a 60 dB (decibel) span, typically from 50 to 110 dB noise level. We must add one more condition. The relative value (1) we read at the bottom of the span must be as accurate as the relative value (1000) we read at the top of the span. Now, let's compare linear and logarithmic scaling using U.S. currency as the physical parameter that is measured.

U.S. coinage and currency spans a range of $0.01 to $100 or 80 deciBels. A logarithmic or dB scale display of this numeric range would place the various coins and bills at about equal spacing. Attempting to express the same range of numbers on a linear scale (with the same graphic resolution for the upper $10 to $100 currency range) would result in losing all comprehension of the value of the coinage.

Now we can read $0.01 (–40 dB re 1$) just as accurately as we can read $100 (+40 dB re 1$). What's more, the 2 dB subdivisions are equally spaced, so we can accurately interpolate any value. We can estimate a reading at the bottom of the scale as accurately as we can estimate a reading at the top of the scale. This is exactly what we said we needed! Isn't that simple? Unfortunately, the minute we call it a logarithmic scale, we scare everyone away, and they never understand it. So we won't talk about it. Suffice it to say that 20 dB represents a factor 10, 40 dB a factor of 100, –20 dB a factor of 0.1, –40 dB a factor of 0.01, etc. An alternative to the *linearly graduated* decibel scale is the *logarithmically graduated* linear scale shown here. Either alternative would provide almost the same accuracy of interpretation.



Now, back to the first question. WHAT is a level recorder? It was the first major product developed by Brüel & Kjær to record voltage levels on an evenly divided, preprinted dB scale. It also featured interchangeable potentiometers that allowed users to select spans of 10, 25, 50 and 75 dB, and even a linear span. They enabled the level recorder to graphically record everything from reverberation time measurements that require a wide dynamic range, all the way down to special situations that might require only a 10 dB span. The chart motor drive could be coupled to both oscillators and analyzers to completely automate and synchronize a frequency analysis or frequency response measurement.

Nielsen. It was ingenious because of its simplicity. I know that Nielsen was aware of H. V. Braunmühl's description (from 1935) of the principle behind the Neumann level recorder which was developed later. The principle is: *The fixed contacts of a logarithmic potentiometer are scanned using a moving element system, where the voltage one is interested in measuring is fed to the top of the potentiometer. The voltage one is after will therefore be changed logarithmically towards a fixed reference voltage. The moving element system now seeks to find a contact on the potentiometer where the voltage is the same as the reference voltage. By connecting the moving element system to a pen that plots on a strip chart that moves at a constant speed, one can plot the logarithm of the voltage as a function of time.* An exponential curve, e.g. the reverberation time in a room will be plotted as a straight line. Braunmühl's recorder was also ingenious and the mechanical construction of both Neumann's and later Siemens was very robust. It was, in fact, revolutionary in the field of room acoustics. In the mid-1930s, the Neumann recorder was generally not available. That was when Nielsen developed his recorder, the principle of which is shown in Figure 3. The logarithmic potentiometer is a chain of T-links where the resistor is tap water placed in an arc. The deflecting system is a common moving coil element with a pointer that dips in the water potentiometer. The readout is achieved optically using a series of mirrors. On top of the apparatus, a frosted glass plate is mounted, where the values can be read-off or traced on a piece of photosensitive paper. The complete system is very simple and has many advantages: 1) extremely high speed (approximately 2500 dB/sec; 2) aperiodic damping; 3) very high dynamic range selectable between 25 and 100 dB; 4) high accuracy; and 5) compared to the Neumann recorder, there is no wear, and it could run forever.

The idea of making a logarithmic potentiometer using water was not completely new. I recollect that Larris informed me in 1943 about the description of a logarithmic liquid potentiometer in *Analen der Physik*. It was built like a bath filled with liquid as a large surface, one end of which was broad while the other narrow. One can surmise that it could not have had a dynamic range larger than 20 dB. Also, such a potentiometer would not be highly sensitive to small deviations from the horizontal plane. The ingenuity about Nielsen's T-link construction is that the operable range can be quite large; 100 dB is not a problem. Small deviations from the horizontal plane are not catastrophic either. Another advantage of a liquid potentiometer is that the damping is so simple. One can achieve the desired damping by adjusting the depth of the pointer tip into the liquid (see Figure 3).

I myself used this recorder (only one sample of which was made) in order to investigate among other things, P. Morse's postulate that the absorption of a sound wave, which propagates parallel to a highly absorbent surface, is zero. This is highly significant for

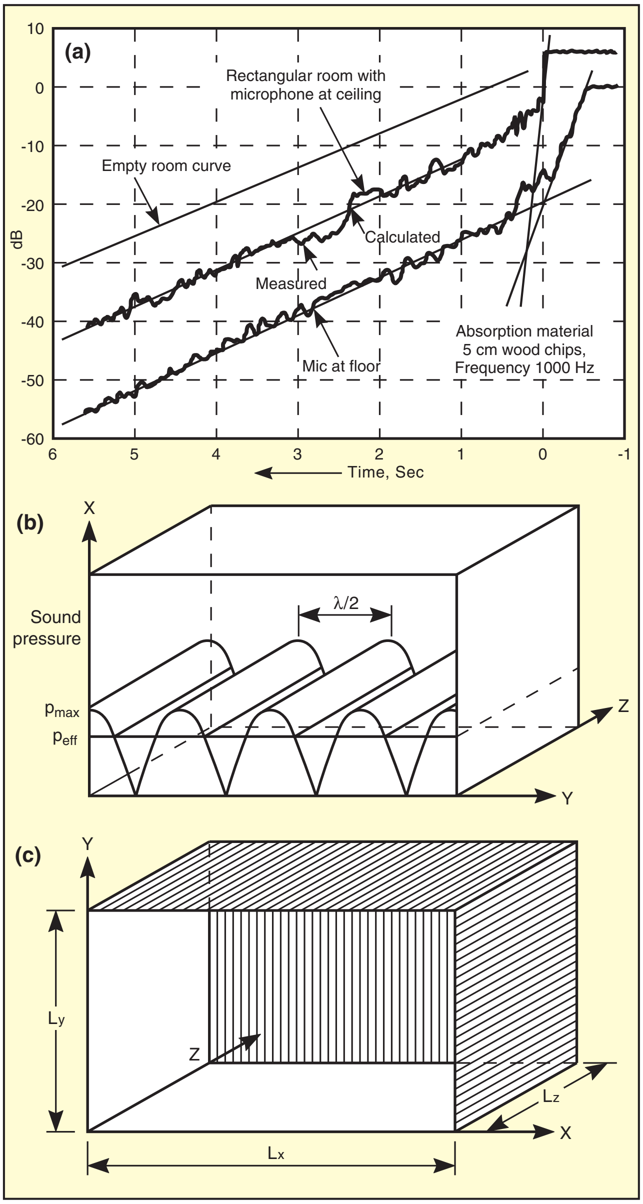


Figure 4. (a) Reverberation curves recorded with Nielsens's level recorder; note the detail. (b) Standing wave moving parallel to absorbing material covering the floor in a 6 × 6 × 4 m concrete room. (c) Only rectangular rooms, where each wall section has the same acoustic impedance, can be calculated by solving the wave equation.

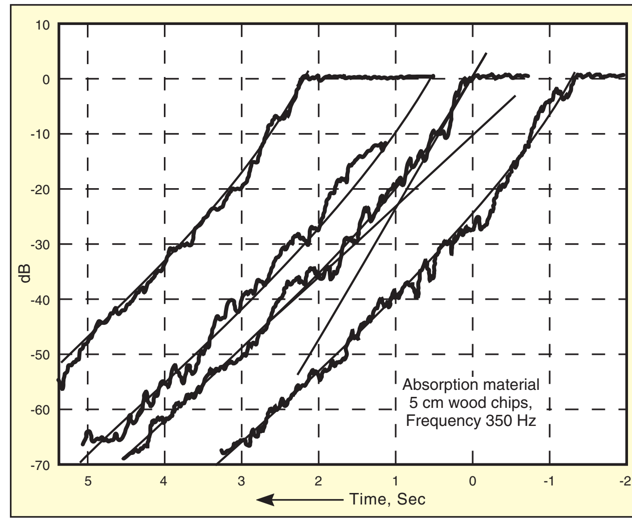


Figure 5. Reverberation decay times in the same room as Figure 4 at lower frequencies; flutter echo less pronounced. With longer wavelengths, absorption material has better contact with parallel sound waves. That is one reason why flutter echoes are a high-frequency problem.

flutter echoes. We carried out the following experiment: the reverberation time in an empty concrete room was measured at 1500 Hz. The floor was then completely covered with material having very high sound absorption at 1500 Hz. The reverberation time was approximately the same as for the empty room (see Figures 4 and 5). We obtained an absorption coefficient of $\alpha = 0$. There is another theory that predicts one should get ½α, i.e. we should measure an absorption coefficient that is half this value, such as that obtained when measured perpendicular to the angle of incidence. I have never been able to confirm this theory in a large room. On the other hand it is correct for a tube, e.g. a ventilation duct.

An Analyzer for Acoustic Measurements

In 1932 there was a short description in the *Journal of the Acoustical Society of America* (*JASA*) of a frequency selective amplifier, where the selective section was an amplifier with a double T-link (or "twin-tee") in a feedback loop. The T-link was made solely from resistors and capacitors. Viggo Kjær and I thought that this principle could be used for an analyzer where the bandwidth would be proportional to the tuned frequency, very close to the frequency scale of the human cochlea.

As a Danish army soldier in April 1939, I was sent to the dispatch rider school and later drove all around the country on a Nimbus motorcycle. In September 1939 the war broke out when Germany invaded Poland. I was transferred to Skals and drove almost alone on the country roads because of fuel rationing. Fuel was available only for the military, police force and ambulances. All communications to foreign countries in the west were severed. As a consequence we could not get *JASA* either. The edition with the selective amplifier was the last one we received for many years. In November 1939 I was transferred to the military radio workshop in Ryvangen to develop radios for tanks from components one could get in Denmark. I had plenty of time and could also work a little in the evenings. I started on the acoustics analyzer. It was fortunate that M. P. Pedersen made some fine wire-wound potentiometers and Tobias Jensen had developed some useful capacitors. At the radio work shop we had some vacuum tubes suitable for battery operated amplifiers – perfect for use in the analyzer. The world's first analyzer with constant bandwidth proportional to frequency was produced in 1940 as shown in Figure 6. The cabinet construction and the colors were the same as used by the Danish military. We had a light green front panel and the cabinet was a very dark green. We have maintained this color scheme to today. There have been innumerable queries about where this color originated. The answer is quite simple – from the Danish military.

The German occupation of Denmark began on April 9, 1940. The afternoon of April 8, we were aware that something ominous was about to happen as all the ammunition we had for our hand weapons was confiscated. As a dispatch rider I had an automatic pistol and the cartridges had to be handed over. We weren't given any explanation, but it came the next morning. Prime Minister Stauning had given up all resistance to the German invasion and would make sure that no Danish soldier would shoot a German.

In bright sunlight I discussed what we should do with I. Thomsen, a colleague from the university who was in the same situation. According to the Geneva Convention, the Germans could freely use our manpower. We saw ourselves working as electronics engineers for a German factory. As that idea did not appeal to us, we considered moving to Sweden. In order to delay the possibility of the Germans getting hold of us, we thought it was best if we could remove our draft cards from the barrack's card file. Around 10 o'clock I went to the office where there was a confused young man. He was told a lie that Thomsen and I were to go on a secret mission and therefore we should have our draft cards without any receipts. The young man could very well appreciate that, especially because German airplanes were flying low just over our heads.

At 12 o'clock we saw a German officer driving up in a motorcycle sidecar to the barracks on Østerbrogade. He proclaimed that he was now the man in charge of the barracks. Here stood a single German with pistols on his belt in front of several hundred Danish soldiers

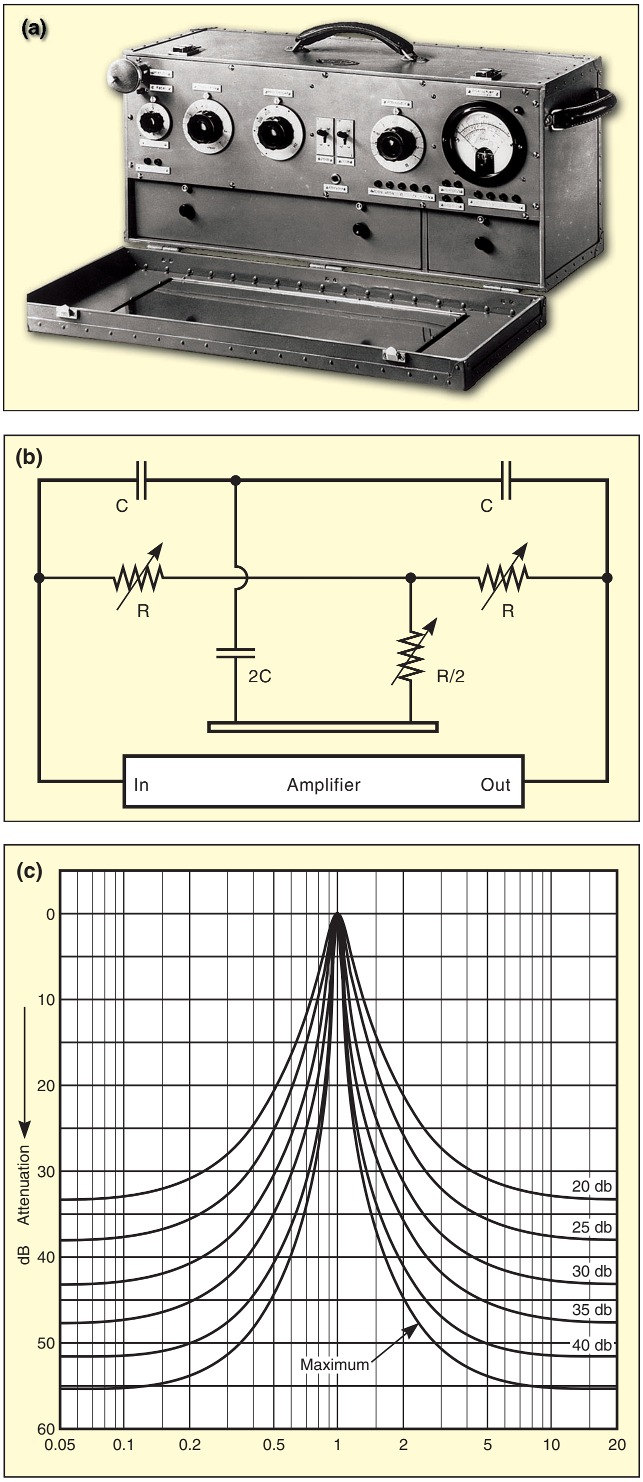


Figure 6. (a) World's first acoustics analyzer (constant percentage bandwidth analyzer). Developed and built by the Danish army's radio shop in Ryvangen in Copenhagen, December 1939-February 1940. (b) Feedback loop used in the analyzer for variable frequency. Three variable resistors continuously covered one octave and capacitors were switched in steps for whole octaves. The analyzer was battery powered and was made in two copies. (c) Filter selectivity curves.

without ammunition proclaiming that now it was his word that was in force. By this time I had enough; I went over to the workshop, collected my private belongings and the components that I had worked with, packed my uniform in a carton and cycled back home to Lyngby. A couple of days later Hitler decided that all the personnel should be sent home. I was now afraid, as the missing draft card would cause problems for our demobilization. I went again to the barracks office, where there was again a confused German soldier, who at once became suspicious about the situation. I mumbled something about Zahnartz, to which he agreed that the

What's a BFO?

BFO is the abbreviation for "beat frequency oscillator," an analog instrument developed by Brüel & Kjær to generate an audio frequency sinusoidal voltage of adjustable amplitude and frequency. Just as a level recorder enables us to record a wide range of amplitudes without changing scales, a beat frequency oscillator allows us to sweep through a broad range of frequencies, continuously.

Most bench sine generators provide several ranges of frequency, each spanning about a 10:1 ratio of highest to lowest frequency. All Brüel & Kjær oscillators provided a frequency ratio of 1000:1. They were available in ranges of 2 to 2000 Hz for vibration applications, 20 to 20,000 Hz for acoustics applications, and 200 to 200,000 Hz for ultrasonic applications.

A BFO actually employs two high-frequency oscillators, each operating at a frequency many times greater than the desired sweep range. One operates at a fixed frequency, the other at a variable frequency differing from the fixed frequency by the desired output frequency. The two oscillator signals are mixed (imperfectly multiplied), producing tone components at the sum and difference of the two oscillator's frequencies. This mixed signal passes through a low-pass filter that rejects all but the difference (or beat) frequency component.

While the frequency ratio swept by the variable high frequency oscillator is small, the span of the swept beat is 1000:1. The high frequency tones employed are very stable because the component oscillators are virtually identical and are contained within a temperature stable cast aluminum housing, so that any thermal drift is canceled out. This results in a very stable beat frequency.

The variable oscillator's frequency is determined by a custom-designed tuning capacitor with capacitance varying logarithmically with rotation. Turn the variable capacitor, and the BFO generates a sweeping output frequency. However, the story becomes even more interesting when the BFO is integrated with a level recorder. The BFO provides a flexible drive-cable connector that lets the motorized level recorder turn the variable capacitor of the BFO to tune it.

All Brüel & Kjær BFOs also provided a unique feedback control input. A signal applied here causes an amplitude compressor circuit to adjust the BFO's output so that the feedback signal amplitude is held constant as frequency changes. If you are testing loudspeakers, you simply provide a reference microphone signal as the feedback and the BFO output amplitude will automatically change to maintain a constant sound level amplitude at the loudspeaker. For vibration testing, you feedback an accelerometer signal to produce a constant acceleration level on a shaker.

Figure 7. Beat-frequency oscillator (left) and line-powered frequency analyzer with two selective sections (six variable resistors and 8 × 6 fixed capacitors). Standing-wave tube (front). All were made at the army's workshop in Ryvangen in 1942 and were beautifully crafted.

cards should, of course, be in the right place.

I continued at LTT and together with Viggo Kjær developed a line-powered analyzer with higher selectivity than the battery powered version. Besides that, we had developed a good heterodyne tone generator (beat frequency oscillator) with linear frequency modulation (warble tone), such that all the resonance frequencies of a room could be equally excited. The skilled technicians

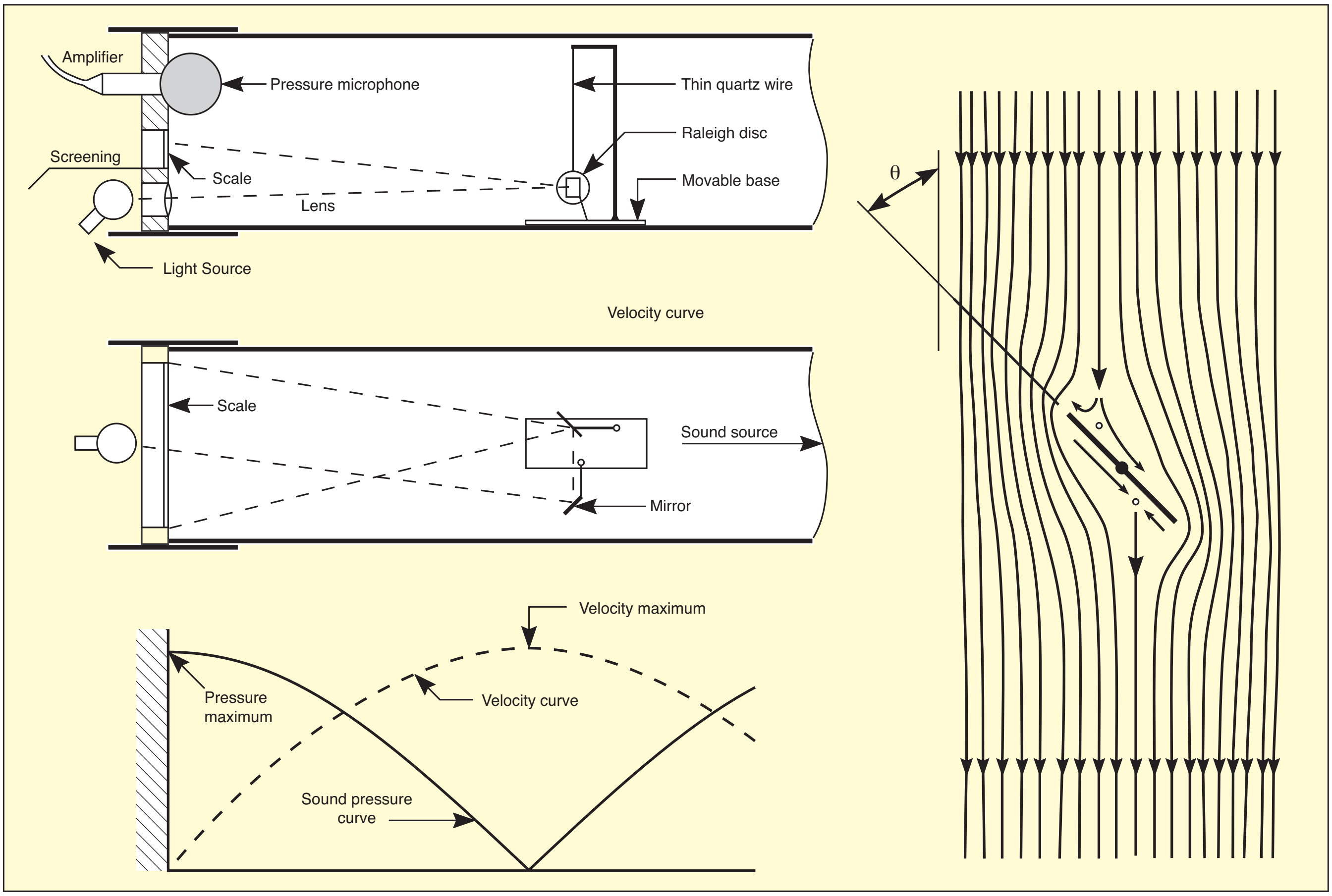


Figure 8. J. Oskar Nielsen's setup for calibration of standard microphones by using a Rayleigh disk. He obtained an accuracy of ±0.2 dB; but one must correct for both the thickness of the disk and temperature.

employed at the army radio workshop were now unemployed after the German occupation, so we made an agreement with the radio workshop to produce measurement instruments (see Figure 7). We sold them in Denmark, Sweden, Norway and Finland and established many good alliances with Nordic acousticians.

J. Oskar Nielsen's Standard Microphone

In the years 1930-1935 there was a problem at LTT in measuring the sensitivity of microphones. Some 45 years earlier Lord Rayleigh had described two methods: The reciprocity principle and the Rayleigh disk. One could not understand the first one, while the second could not be used if there was a draft in the room. We used all types, e.g. thermo-phone, pistonphone or other strange methods for determining the sensitivity of a microphone.

J. Oskar Nielsen was the oldest assistant at LTT and was rather clever. His scholastic average in his senior year at the university was 7.87 (on a scale of 8), which was higher than my future associate Viggo Kjær's 7.84. Both of them belonged to the university elite. After they graduated, these records were never again achieved. Unfortunately, Nielsen died very early.

LTT wanted to have a 'normal' microphone to calibrate all other microphones in Denmark. A very expensive Sound Cell microphone was purchased from Brush Electronics in Cleveland, Ohio, U.S.A. A calibration certificate was provided with it, and needed to be re-checked.

At LTT there was a large diameter, long tube for sound absorption measurements at low frequencies. The microphone to be calibrated was placed at the end plate, and a Rayleigh disk was suspended at a quarter of a wavelength distance, using a quartz wire through the side of the tube, such that the quartz wire could be rotated as shown in Figure 8. The Rayleigh disk had a reflecting surface and, using a light/mirror arrangement, one could see at the end plate if the Rayleigh disk was at an angle of 45° from the longitudinal axis of the tube. This angle is where the sound waves produce the maximum moment on the disc. Room drafts did not affect these measurements and one could achieve maximum accuracy. Results from the first measurements were only a few tenths away from the American calibration.

The 'normal' microphone was locked-up in a cabinet by engineer Christensen, the laboratory watchman. A couple of years later I needed to calibrate some other microphones that were to be used at the Broadcasting House. I could not get anything to work, so I decided to recalibrate the 'normal' microphone using Nielsen's equipment. It showed that the Brush microphone sensitivity had dropped by 10 dB. I was blamed for having destroyed the 'jewel.' No one could imagine that a microphone in a locked cabinet could deteriorate, and as I was the only one who had a finger in the pie, I must have somehow damaged the microphone. Fortunately, I soon read a notice that Rochelle crystal microphones should be stored in a chamber, which was sufficiently humid to avoid dehydration of the crystal.

P. O. Pedersen's Favorites

P. O. Pedersen added a requirement to the university curriculum for the electronic engineering majors that required several months of work (plus summer holidays). The electrical engineering majors had smaller projects. P. O. Pedersen argued that, because of these larger projects, electronics majors could claim to have the English M.Sc. degrees while the electrical engineering majors could claim the B.Sc. degrees. One could not use the term 'Civilingeniør' in English as it meant a Civil Engineer (a construction engineer). To get to know his students personally and simultaneously get an idea of how much they had learned, all the students were required to give a presentation on a topic of their choice after the course was over. Of course, it had to be related to what had been taught. I had just found a small thin book about building acoustics in the library written by one of Erwin Meyer's assistants, Arnold Schoch. I talked a little about building acoustics on the basis of this book. This led to P. O. Pedersen asking me if I would take on an examination project dealing with the measurement of vibrations using a microphone placed in a tube lined with sound absorptive material as shown in Figure 9. That was a good project as it demonstrated a lot of

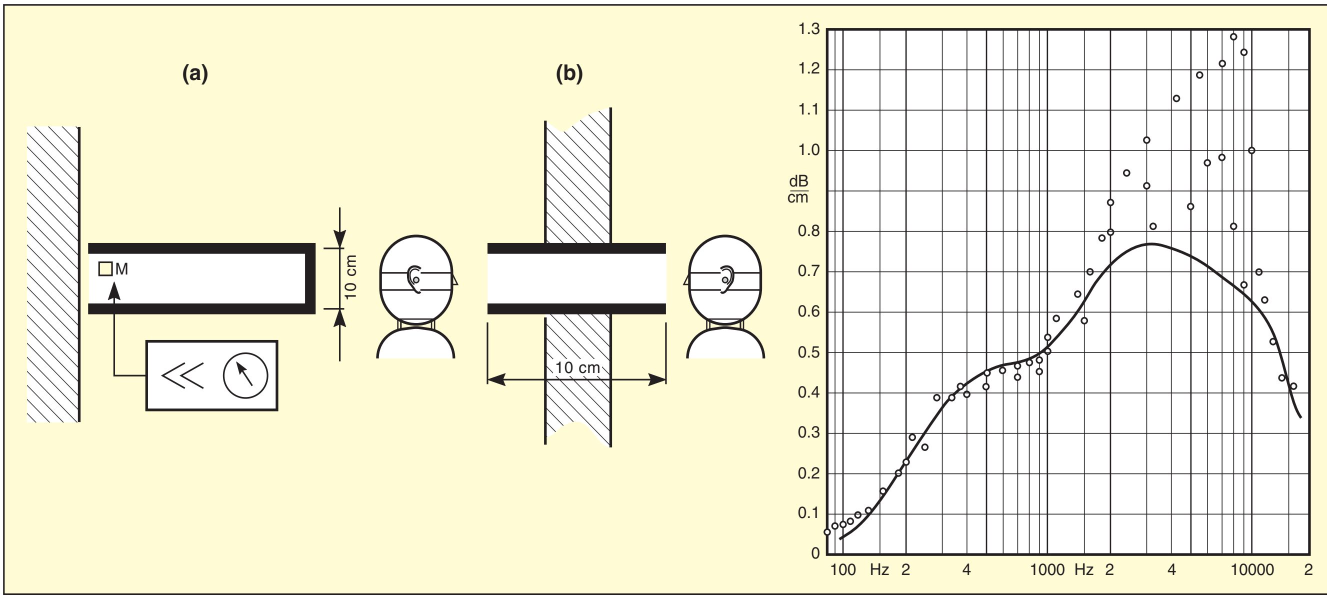


Figure 9. (a) P. O. Pederson's idea to measure the vibration amplitude of wall with a microphone in a tube lined with sound absorptive material. (b) 12-cm tube lined with sound absorptive material placed in a heavy wall. It was very difficult to communicate through the tube. Graph shows measured absorption. High attenuation at high frequencies makes speech difficult.

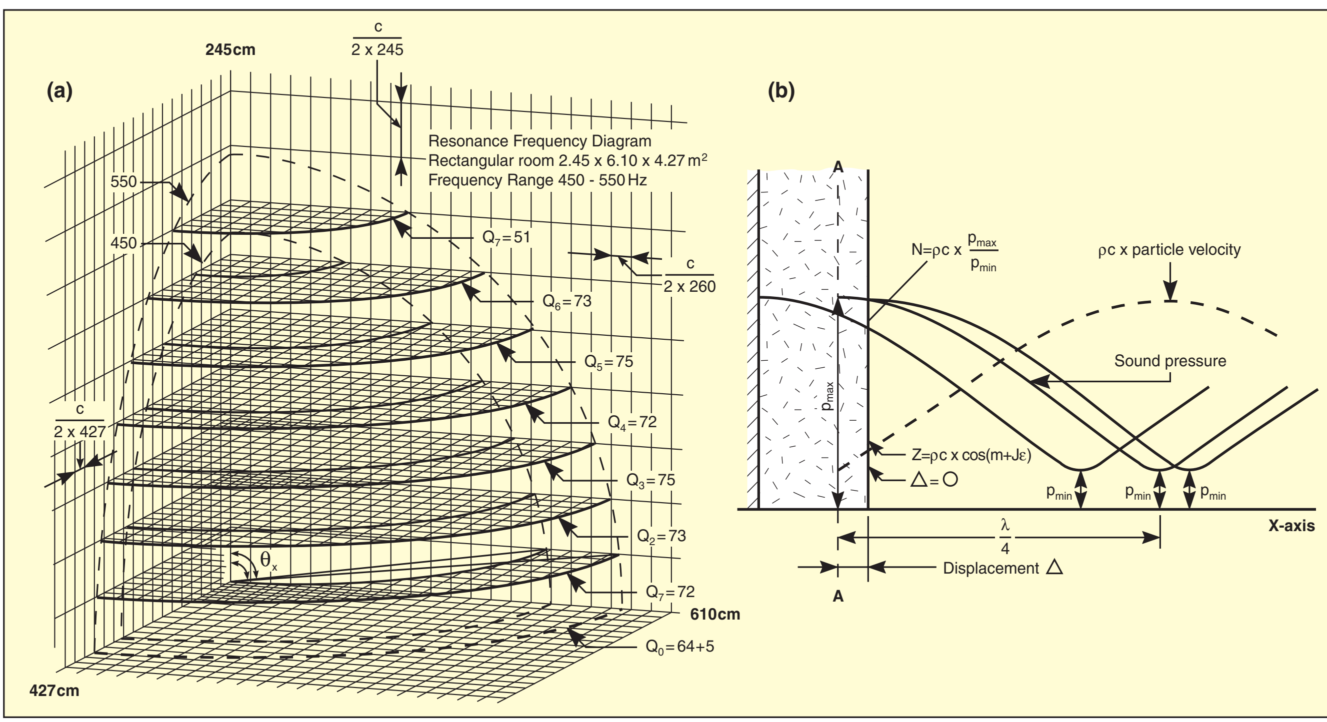


Figure 10. (a) Frequency of a standing wave in a rectangular room (distance from center) and the directivity. Rapid increase in numbers stems from increasing frequency. (b) Impact of standing wave on porous absorption material. From position at p_{min} and ratio p_{max}/p_{min}, complex acoustic impedance can be determined. Real impedance is found in Plane A-A.

interesting phenomena. For example, we placed a short tube lined with sound absorptive material in a thick wall. Individuals at either end of the tube could see each other at a distance of only 50 cm, but could not hear each other very well. It was really weird. A couple of students each year were given ideas for special projects to work on. They included Viggo Kjær, who was the cleverest member of the team by far, to work on a project in the field of amplifiers.

Sometime after the publication of the "Lydteknisk Undersøgelser" was completed, P. O. Pedersen suggested that I should start working toward a doctoral thesis. I was, of course, interested and had an idea for a topic. My project of choice was inspired by the work of Richard Bolt and especially Chinese professor Maa Daa You (mentioned later). I was of the opinion that by measuring the complex acoustic impedance of the wall structures of a room in a standing wave tube, one could calculate the most important sound fields in the room. We could thus completely dispense with measuring the acoustic absorption coefficients using the room method. P. O. Pedersen thought that was a good idea and would obtain grants for the laboratory, such that I could be employed for a period of 1½ years to carry out the project.

We Thought We Knew All About Acoustics

During the early 1940s, some young engineers from the Massachusetts Institute of Technology (MIT) became interested in room acoustics. They included Richard Bolt, Leo Beranek, Arnold Peterson, Maa Dah You and others. They solved the wave equation with the wall's acoustic impedance as the boundary condition. Therefore, one could follow in detail each and every sound wave as a function of time; however, only in rectangular rooms and only when all six room surfaces had the same acoustic impedance. A lot of work was done and many articles written, but one could not use the theory for common rooms which did not have the form of

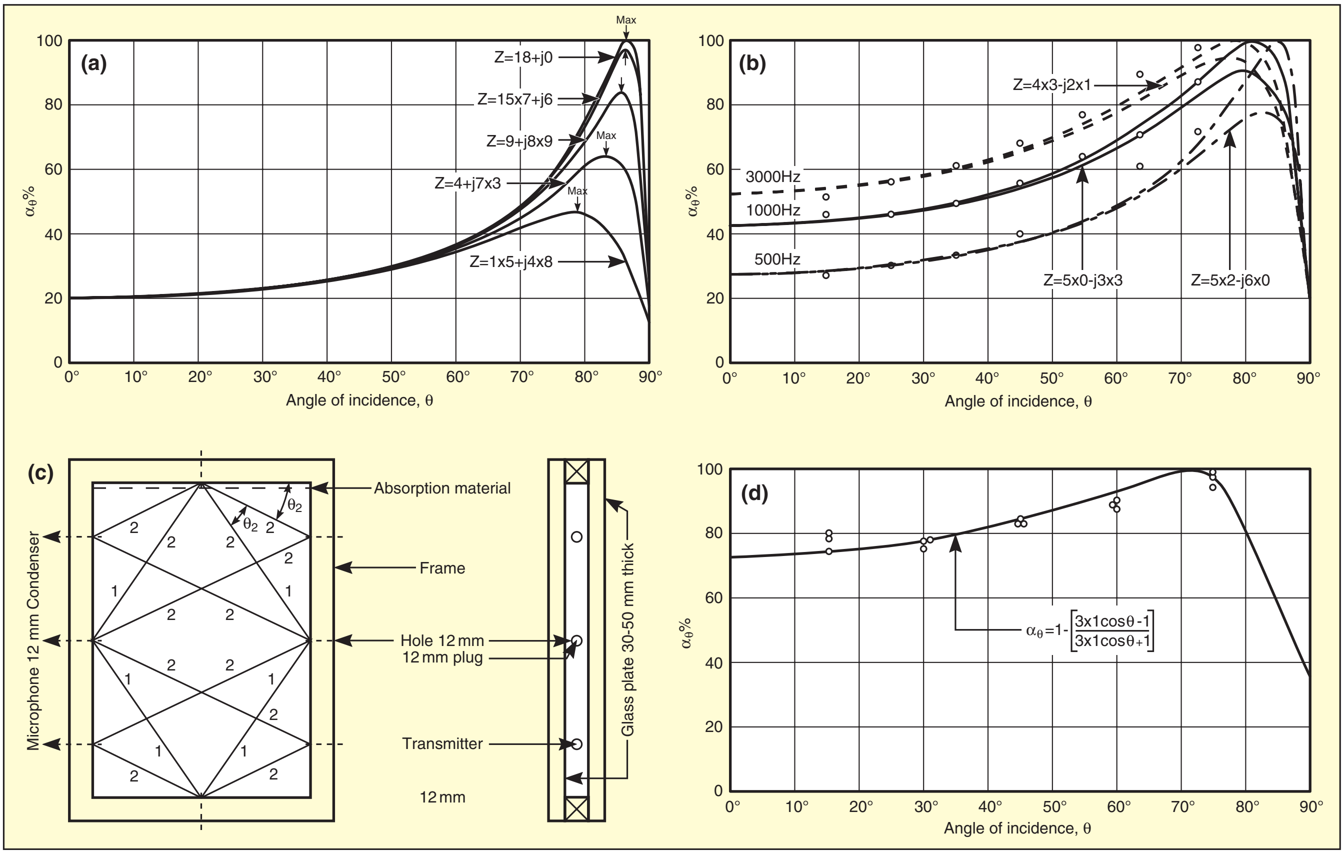


Figure 11. (a) Solid curves are F. V. Hunt's theoretical curves for increase of absorption with angle of incidence. (b) Dots are measured results made by Hunt in 1935 and measurements made at Chalmers in 1944. (c) Two 30-mm glass plates form a very flat room. A slow gliding tone excited resonances of standing waves in the enclosure. (d) Absorption for angles between 75° and 90° could not be experimentally verified.

a shoebox or when the surfaces were not homogeneous.

Personally, I found to my amazement that sound waves of different frequencies did not interfere with each other. I tried to simplify the calculations by considering only the real part of the impedance instead of the complex impedance that exists at the surface of the wall. Deep inside the absorption material one finds a region where the impedance is real as shown in Figure 10. It is also in this plane that reflections take place. Naturally, the dimensions of the room should be modified accordingly. I am convinced that it is more correct to determine the dimensions of the room from the virtual surfaces where the reflections apparently come from, rather than operate with complex impedances at the physical wall surfaces. My simplification did not, however, solve the problem. We could only calculate the absorption of rectangular rooms with homogeneous surfaces.

We were also very interested on the dependency of absorption on the wave angle of incidence to the absorptive material. We experimented a little with directional microphones. That did not work at all. We then used our knowledge of resonance frequencies in a rectangular room, which we constructed as shown in Figure 11. Here we could excite some two dimensional resonances between two thick glass plates with waves having a specific angle of incidence relative to the pair of glass plates. We covered one end of the test space with some absorption material and from the shape of the resonance curve we could determine the absorption coefficient α for a specific angle of incidence. We measured the absorption both in the empty space and in the space with some material mounted.

P. M. Morse had a theory for the dependency of material absorption on the angle of incidence. The results of this theory are plotted as curves on the three graphs in Figure 11. Graph (a) is only for theoretical values for 90° incidence on absorption material with α_0 = 20% for different complex impedances. Graph (b) shows the measured values as points. We could not experimentally verify Morse's hypothesis $\alpha_{90} = ½\alpha_0$. Our results in the test space show that α_{90} is very close to zero as shown in Figure 11b and 11d. I utilized this information for the large ventilation ducts installed in the Radiohuset (Radio House) on Rosenørns Allé. What was important was that we got to understand flutter echos, which we could now identify, measure and thereafter prevent from occurring in acoustically treated rooms.

I was very interested in Leo Beranek's and Maa Daa You's work on the wave equation. It was a turning point in acoustics. Before Lord Rayleigh, acoustics was practically a mystery. As only a few understood Lord Rayleigh's work, it was W. C. Sabine, with his definition of reverberation time, who gave us a tool we could use in practice. But even here there were many inexplicable phenomena. The last bit of mysticism and superstition disappeared fully with the wave equation. I met Leo Beranek in Boston in 1950 and Maa Dah You in Beijing in 1953. Since then I have met both of them almost yearly. Maa Dah You disappeared for five years under the Chinese Cultural Revolution. Leo Beranek is a bit older than I and Maa Dah You is in between. This resulted in Maa Dah You calling Leo Beranek "my elder brother" and me "my younger brother." This is very honorable in Chinese culture.

When I was in China in 1953 I gave ten lectures on acoustics over a two week period at the university (these were my lectures from Chalmers) with Maa Dah You as the interpreter for 300 invited guests. I have met a large number of these guests several times over the last 40 years. Many have been given scholastic chairs throughout China.

P. O. Pedersen at the Center

Fourier has shown that any periodic function can be described as a summation of a series of sine and cosine functions, where the lowest is the fundamental frequency/wavelength and the rest are all higher frequencies. In 1932 P. O. Pedersen was using a new electro-dynamic loudspeaker (which we are familiar with today), to which he fed a 1000 Hz tone, and when the level was increased he could also hear a 500 Hz tone. This was news in those days, as everyone believed according to Fourier that there could not be any frequency components below the fundamental frequency. P. O. Pedersen found and described the fundamental law that caused this. One hunch was that sub-harmonics would be generated, if the loudspeaker was heavily loaded causing the coil to move outside the magnetic field, and thus be subjected to a non-linear force. P. O. Pedersen also made a big wooden model with two pendulums. When the small pendulum was excited, the big one also responded. I think I saw this model in 1939. I tried in 1995 to find it or someone who had seen it, but without success. I have often thought that in 1932 there must have been thousands who worked with loudspeakers, including myself, and who must have heard the sub-harmonics without dealing with them. All were interested in the distortion of loudspeakers, but for most of them it was because of the higher harmonic frequencies. This was typical of P. O. Pedersen to notice the extraordinary in common things that others of us overlooked.

Similarly, it often occurred, when we as young assistants talked enthusiastically about something we had done, that P. O. Pedersen would pose a very simple question, to which we had to admit that we had not given much thought, and our brilliant ideas would fall to the ground. On rare occasions it went the other way. I remember once discussing a very banal problem with him to which I had a very simple explanation. P. O. Pedersen came up with a complicated solution that involved potentials, resonances, complex impedances and differential equations. I insisted that the whole thing could be explained using Newton's second law. P. O. Pedersen was stubborn, and a full day passed before he admitted that it was true.

When the Germans invaded Denmark on April 9, 1940, P. O. Pedersen pretended that he had great difficulties in reading, understanding and speaking German, although before the war he was fluent in this language. Around the beginning of the occupation I happened to be nearby when Professor Absalon Larsen complained to P. O. Pedersen that he could not understand the English news broadcasts that were meant for Denmark. Absalon Larsen's English was not that good and the German jamming stations made the situation even worse. P. O. Pedersen then promptly informed him in Danish of what was going on in the world. P. O. Pedersen made it a point to keep himself well informed regardless of the language.

Telephone Security at Amalienborg

A couple of months after the German occupation of Denmark, P. O. Pedersen mentioned that by connecting an amplifier to the end of a long telephone line, one could hear and understand what was being said in a room with a connected telephone. The telephone company was fully convinced that if the receiver with the microphone was placed on the telephone stand, the microphone was fully disconnected. We examined the situation and to our great astonishment we found that an unused telephone worked as a bad microphone, but not so bad that we could not understand everything that was being said in the room where the telephone was located. The telephone laboratory on Nørregade still insisted that this was impossible. We demonstrated the phenomenon and the telephone employees went away embarrassed. P. O. Pedersen wanted to make sure that the King at Amalienborg could speak freely in the room where he had his telephone without the Germans being able to eavesdrop. I was asked to make a suitable box for isolating the telephone to solve the problem. I made a bottom plate on which the telephone could be placed and a box without a bottom that could be placed on top of this plate. The box was filled with sound absorption materials with maximum absorption in the frequency range shown by V. O. Knudsen to be the most important for speech intelligibility. The box seemed to have enough sound isolation, but one could, nevertheless, hear the telephone ring. P. O. Pedersen went up to Amalienborg with the box and after that I did not hear any more about it.

Hitler's Victory Monument

During Rommel's campaign in North Africa, Hitler started planning a victory monument, which should encompass a hall that was 10 times larger than Saint Peter's Cathedral in Rome. Planning of an enormous marble covered hall with a square floor was started under the auspices of the (then) Labor Minister Ley. At each corner there was a tower. I have never seen the drawings but I was given an oral description. Dr. Ley got the idea that he should consult with the 'guru' in acoustics, Professor Erwin Meyer, to inquire how the acoustics would be in such an exceptional edifice. Erwin Meyer calculated the reverberation time to be 30-40 sec. In Meyer's opinion the hall was not especially suitable for conveying Hitler's speeches. Dr. Ley therefore asked what should be done. Meyer replied that the walls and the ceiling should be covered with a thick layer of rockwool. This resulted in a major dispute; the architects insisted on marble. Meyer was ordered to find a different solution.

Rumors of this dispute reached Copenhagen, where Oelsner wrote to Dr. Ley that he could solve the problem and referred to several constructions. Among them was Grundtvigs Kirke where he was responsible for the acoustics. His method involved building lead panels into the sidewalls; therefore the sound is redirected and becomes clearer in the room. The German architects got enthusiastic about this idea. Minister Ley was not convinced of Oelsner's suggestion and demanded that Erwin Meyer investigate the effectiveness of the lead panels.

Meyer wrote to P. O. Pedersen and asked him to measure the reverberation time in Grundtvigs Kirke. P. O. Pedersen was not very comfortable with this idea and Meyer was informed that, because of the German occupation, he neither had suitable tone generators nor level recorders. But we would gladly help with the loudspeakers and cables. Meyer could easily figure out that we were not enthusiastic about this whole affair, but nevertheless sent three engineers with the relevant electronic equipment to Copenhagen. P. O. Pedersen sent me as his youngest assistant to help the three engineers. He suggested that we should not get involved with the problem, nor comment on the results to the Germans. Neither P. O. Pedersen nor any of the others in the laboratory would meet or talk with the three engineers. We were also indifferent to their measurement results and they never saw our laboratory. The youngest engineer tried to start both a technical and a political conversation with me.

I was never told what came of the whole affair. It might have been rather interesting, as the room in the church where measurements were made had excellent acoustics. Speech could be understood very well and the music sounded really good. The reasons for this were the pillars, recesses and edges, as well as the large irregular surfaces. Although the reverberation times are a bit long, the diffusion is high and therefore the results are quite good. Perhaps some might have believed that the good acoustics were due to the lead panels in the walls.

New Equipment for Universities

The Germans who occupied Denmark needed huge amounts of money to pay for food and other commodities that had to be sent to Germany; they also had to pay for the use of airports and fortifications in Denmark. The way they went about this was simply going to the National Bank and demanding millions of Kroner in return for a letter of credit as a loan from Denmark to Germany. Stauning, who was then Danish Prime Minister, said that it would be rather nice to have some balance in their favor. P. O. Pedersen, who was rather skeptical about the loan, wondered whether he could, instead, buy something from Germany. He imagined getting hold of a variety of scientific measurement instruments, both electrical and optical.

With the help of an assistant at the Laboratory for Telephony and Telegraphy (LTT), P. O. Pedersen got to know what was available. With this knowledge a number of Danish Institutions were contacted to come up with a list of their needs. P. O. Pedersen went to the Ministry of Education with this list but was deeply disappointed in the response of the officers for their lack of understanding. All of these requests should be incorporated within the already allocated budget. New budgets would take a long time. Fortunately those at the Ministry of Finance were more understanding and LTT got two Neumann Recorders and a Freistadt Spectrograph from Siemens and even an electronic clock from Rhode and Schwartz. A number of small institutions also got a wide variety of measuring instruments.

Sound Vases

In 1938 I heard of earthen vases embedded in the walls of some

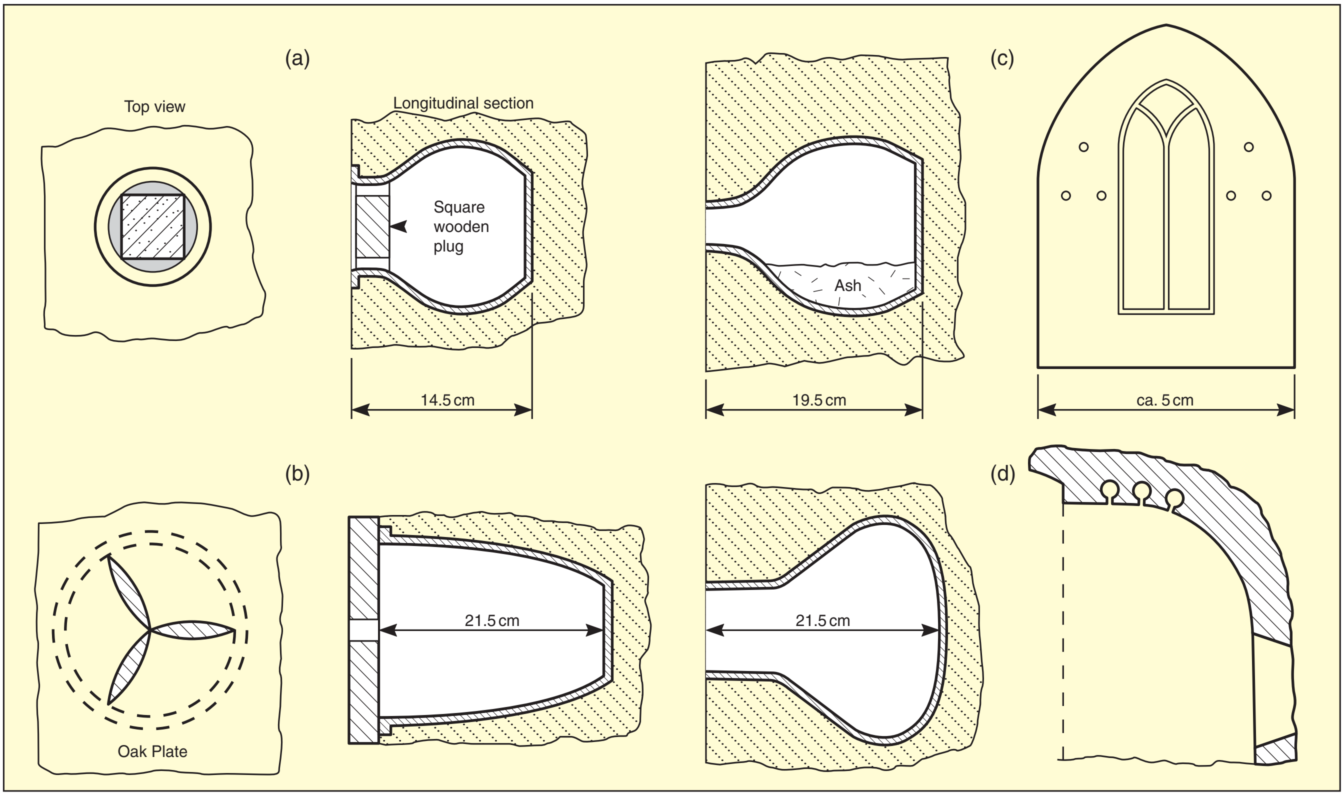


Figure 12. Sound vases from Danish and Swedish churches: (a) Nikolai church in Svendborg with wood square plug in opening; (b) Bjerresjö church in Skåne, oak plate in front. resonance frequency 220 Hz, T=0.4 sec; (c) Vor Frue kirke in Svendborg, resonance frequency 155 Hz, T=0.9 sec; (d) Nylars church, Bornholm, resonance frequency 240 Hz, T=0.45 sec. Drawings are by M. Mackprang from the National Museum in Copenhagen, 1905. Based on these drawings, a series of vases was made in life size. The models were used for acoustical measurements at Chalmers Acoustical Lab.

churches in Denmark in Medieval times. Use of these vases apparently improved the acoustics. There were several churches in Denmark and a couple in Sweden that had them imbedded in their walls (see Figure 12).

The famous Roman architect and builder Marcus Vitruvius, an admirer of Greek architecture in his treatise *De Architectura* about Greek and Roman building art, suggested the use of large earthen or bronze vases to improve the acoustics in theaters. The vases should be finely tuned. They should be placed under the seats and face toward the center of the theater. It is difficult to fully understand the details from Vitruvius's description. I have shown the plan as best as I can in Figure 13.

If this makes any sense, the vases in the churches should help reduce the reverberation times in the closed, hard rooms. On the other hand, it should have the opposite effect in theaters in the open air. The vases should absorb some sound energy from an impulse and a second or two later radiate the sound at the resonance frequency. In 1938 not a single vase was found from Roman times. In 1941 I cycled around Denmark to the churches, which had the sound vases in them and measured the reverberation times in the rooms with a small battery driven apparatus. I then covered the openings of most of the vases that were accessible with cotton wool and tape. Unfortunately, it was impossible to detect even the slightest influence on reverberation.

In 1958 a complete theater with earthen vases was discovered underwater in Nora on Sardinia. Not all of the vases were in place (see Figure 14). I went immediately to Nora with cameras and electronic equipment. It was a fantastic experience to see this theater, which had been untouched for over 2000 years. The Director of the Museum from Cagliari came there as the rumor spread that I knew something about the vases. He became very unfriendly when he suspected that there was something special about the vases. So, instead of offering to collaborate, he forbade me to take any photographs or make any drawings or any acoustic measurements, unless I executed a document giving him the right to publish everything I discovered under his name exclusively. I naturally would not sign and therefore I had to return home without any photographs or measurements. When the Director left on summer holiday I returned to Nora. The custodian there was given instructions to allow local inhabitants and all tourists except Scandinavians to inspect the theatre. But we got around this barrier with a 1000 lire bribe.

The vases were very similar to those described by Vitruvius and almost identical to models I had already measured. Measurements on the originals therefore did not reveal anything new. We can still conclude that the use of these vases did not have any influence on the acoustics. Earlier I wrote brief articles on the acoustical initiatives of our ancestors. These articles and the information on vases resulted in David Lubman from Los Angeles starting a sub-committee on ancient acoustics for the Acoustical Society of America. Dr. Lubman was also interested in the acoustic phenomena around the Mexican step pyramids. He has urged me to publish articles on the measurements made on several vases in both Denmark and Sweden. I feel that it would have been more exciting if we had found something positive. In reality we have not found any evidence that suggests that the use of these vases in open theaters or the sound pots in churches improved the acoustics in any manner.

'Radiohuset' on Rosenørns Allé

After the scandal with the 'Stærekassen' and its tragic consequences, one had to make sure (I was informed as such) to avoid such a recurrence when the new Broadcasting House 'Radiohuset' was to be built. Vilhelm Lauridsen was chosen as the architect. He was not only a clever architect but had also demonstrated the ability to cooperate with the technicians. Professor Nøkkentved was responsible for the technical side of the building. It was his suggestion that the roof over the large concert hall should be an impressive steel structure. P&T (Post & Telegraph) would not take the responsibility for the acoustics, but would willingly make all the measurements that were necessary. Nøkkentved, who was a good physicist and sang in the Holte church choir, took over the project and was responsible for the acoustics in the studios, as well as for the sound insulation for the environment and ventilation systems.

As the construction started making progress, one had to decide in

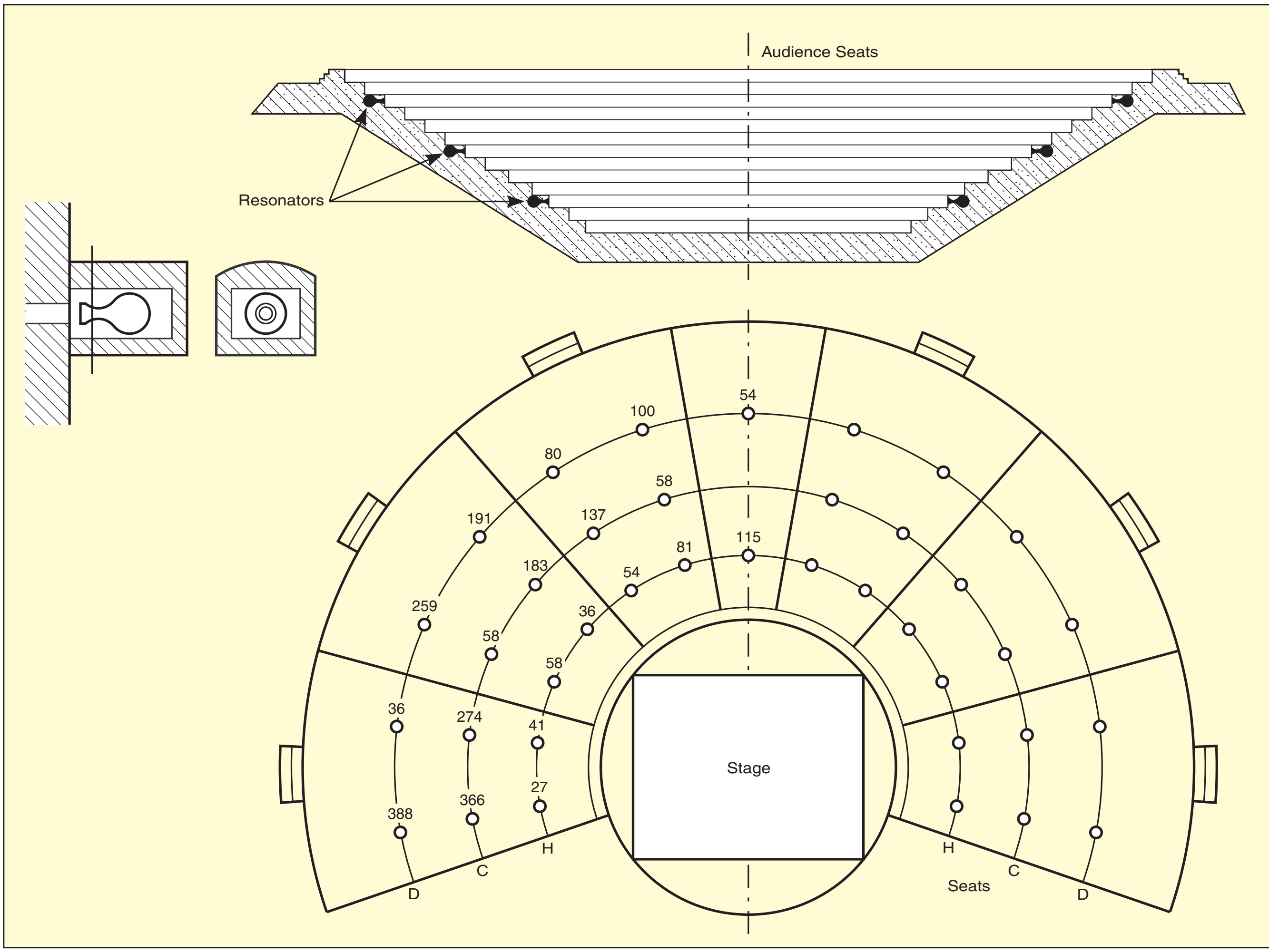


Figure 13. The drawing was made in accordance with what we think Vitruvius meant. Vases were situated under the seats with openings pointed to the center. Each vase was tuned to a different frequency according to a complicated procedure.

Figure 14. Large sound vases as described by Vitruvius and found in Nora, Sardinia, in the late 1950s. Vases are about 2000 years old.

the beginning of 1941, how to cover the inside walls of the studios. Vilhelm Jordan, who got his Doctorate (dr. techn.) in 1941, had left for Ålborg to start an independent consulting business, but under the German occupation it was difficult to make ends meet. With P. O. Pedersen's mediation, Jordan was employed with P&T to carry out the acoustic measurements in the new 'Radiohuset.' Jordan established a nice laboratory on the 3rd floor of the 'Radiohuset' facing Rosenørns Allé. It wasn't long before he started giving good advice concerning the design of the studios.

In my opinion as well as other's, it was an excellent solution, but it did not go down well with Professor Nøkkentved. These two gentlemen had quite different personalities; however, they had agreed to get the job done as best as possible. As a result Nøkkentved asked me, who was an assistant at LTT under P. O. Pedersen and studying for my doctorate, if I would help him with the problems at the 'Radiohuset.' I met with Jordan, (who had been my teacher and later became a very good friend) and told him that from now on I should help Nøkkentved, i.e. have responsibilities for all the acoustical measurements. It was rather unpleasant for me and Jordan was both angry and disappointed to have been slighted. But in a matter of an hour we had resolved our personal problems.

I was very much interested in the sound fields in studios, as they became a part of my doctoral thesis. Our 'bible' was V. O. Knudsen's *Architectural Acoustics*, published in 1932. I always started with the reverberation times (RTs) suggested by Knudsen. The studios already had oblique ceiling sections and nonparallel walls. Therefore there were not many problems with flutter echoes in the studios, but they were evident at many other places such as in the corridors.

When a studio was finished it had to be qualified and hopefully accepted. One invited a good singer, pianist, violinist or a trumpeter, to sing and play. Three dignitaries, Erik Tuxen, Lagny Grøndahl, and head of the Bruun office sat down and evaluated the studio. It turned out to be very difficult, as these gentlemen could not differentiate between the faults of the soloists and the room acoustics. I tried to get them out of the studio and listen via headphones. But that was out of the question. We would typically alter the inside wall covering for up to five times. On a couple of occasions, when I thought that the studio was OK, it still had to be modified three or four more times. When that was done without the studio being accepted, I changed it back to the original configuration and suddenly it was perfect. Naturally, I became skeptical of the jury, because the studio with an irregular RT as a function of frequency was judged to be better than one with a uniform RT over the frequency range.

I had a talk with Erik Tuxen, who could appreciate the problem

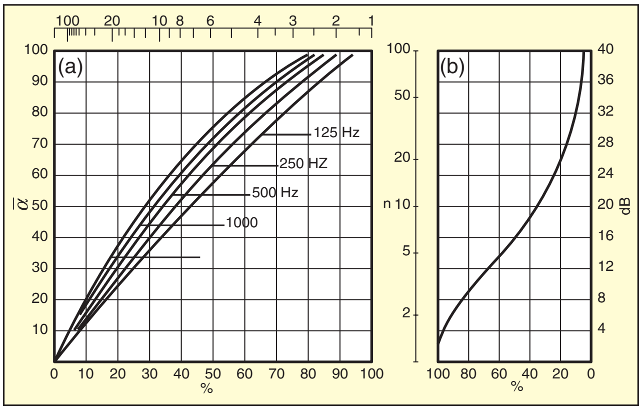


Figure 15. (a) An acoustic absorption measurement in a standing wave tube at perpendicular incidence. You can convert α to the absorption which you get by measuring in an IEC standardized test room. The base for these experiences is a long series of measurements made both in LTT labs and in the Radiohouse at Rosenørns Allé, Copenhagen. The curves are valid for porous materials like carpets, textiles, and absorbing material behind a perforated plate. It is not valid for membrane absorbers where absorption depends on movement of the front plate. (b) Absorption α in a standing wave tube when you measure the ratio n directly, $n=p_{max}/p_{min}$, but also when the ratio is expressed in dB. This is convenient when you use a sound level meter in connection with the standing wave tube

and admitted that it was almost impossible for him to differentiate between the room and the soloist. He suggested relying heavily on the RT measurements and diffusion. I started asking the soloists and the singers to be more consistent in their replies. Engineer Lauridsen, who was responsible for the microphones and their positions, was of great help. The result was that the opinions of the esteemed critics were ignored and we used the performing artists to judge the acoustics. It turned out that the optimum RT was somewhat longer than that recommended by V. O. Knudsen, whereas the balance between the high and low frequencies was not that critical. So all the studios have an RT 20% longer than normally recommended. What the audiences heard was left to engineer Lauridsen. For the music to be 'dryer' the microphones had to be closer to the violins, and for more timbre they had to be more remote. I also suspected Lauridsen and Heegaard manipulated the frequency characteristics of the hall in the control room.

We also made quite a few flutter echo measurements mainly in halls and corridors. These spaces were very heavily acoustically damped and consequently especially sensitive to flutter echo. As we know there is very little coupling between the various waves in a room, it is quite natural to expect that a single wave that incidentally happens to move around and is reflected from the wall elements with little absorption would have a very long reverberation time. If the room is simultaneously highly damped and has otherwise a short reverberation time, the contrast would be high and flutter echo would clearly become apparent.

At the end of 1942 Professor Nøkkentved and I stopped working for the 'Radiohuset.' What lessons had we learned?

- Dignitaries cannot evaluate small studios. They cannot differentiate between the faults in music and the faults in the room. Instead, use the performing artists or measurements of reverberation times, diffusion, and even RASTI (rapid speech transmission index).
- Reverberation times should apparently be 20% longer than the values that have been used normally.
- We found that the variation of reverberation time as a function of frequency is not critical at the low frequencies. For example, a parquet floor on beams could have very high absorption between 100 and 200 Hz without having any adverse effects.
- We had ample opportunity to measure absorption materials in the studios and compare them with measurements using a standing wave tube. We also got some German results. On the basis of all this material we made the curves shown in Figure 15. In my opinion these curves can replace many sound measurements in a room by using measurements from a standing wave tube and converting them to room absorption values. As we often use a sound level meter to receive the signals from a microphone when carrying out standing wave tube measurements, the curve of figure 15(b) shows the absorption in percent against the dB scale read from a sound level meter.
- Most importantly, we confirmed the golden rule in acoustics: "Never have two parallel reflecting surfaces in a room." Naturally, the floor/ceiling problem is the most difficult to solve.

Before I leave my discussion of the 'Radiohuset' I would like to mention two individuals who had considerable influence on the project. Finn Juul was a young architect who worked on the 'Radiohuset' for architect Vilhelm Lauridsen. My job was primarily to achieve the best acoustics in the studios, i.e. using covering on the walls, ceiling and the floor to absorb the sound and also to spread the reflected sound such that the reverberant sound was diffuse. This required close cooperation with the architects who should not only approve the design but also get the work done. Vilhelm Lauridsen was an extremely friendly and nice gentleman, but rarely had time to listen to a young engineer. Therefore this became a job for Finn Juul who had very fixed ideas. Many could be somewhat offended by his violent temper as he was outspoken on the mental faculties of others. I respected his definitive tastes and his work as an artisan.

I had a very fruitful cooperation with Finn Juul. A typical conversation follows: I requested a wall made from vertical slats (in staircase form) such that the wall elements would not be parallel to those on the opposite side. Finn Juul replied: "You can have it as you wish, but explain to me why, so that I understand, and how slanted should the elements be?" I told him a little bit about flutter echo and that I preferred to have the elements at an angle of 10°, but I will accept 8°. "Good, you get 10° and exactly as you had asked for. Come again tomorrow and approve my draft," replied Finn Juul. It took all of three minutes without further discussions. It was more difficult with the other young architects. When one returned with the drawings that had to be approved, they were often not finished as they just needed to talk with Vilhelm Lauridsen, or they had second thoughts and came up with another suggestion than what we had agreed upon. Finn Juul never conferred with anyone about anything or speculated endlessly. He was a very competent co-worker.

The other person I would mention is Jørgen Gravenhorst. He qualified in 1937 and became an assistant to Professor P. O. Pedersen at LTT and was thereafter employed with the Post and Telegraph Radio Service. He was a good electronic engineer and a clever craftsman.

Shortly before the war, there was a great demand for high dynamic range of all the components in the radio transmission chain, e.g. noise and hum free amplifiers. Radio studios should be highly soundproofed. Tape recorders and moving coil microphones could not be used as they were highly vibration sensitive. A lot of effort was put into improving materials for records and their associated pickups, tape recorders and the surface treatments for the tapes as well as recording and playback heads. Several companies tried to make compressor/expander solutions, e.g. Ortofon.

The State Radio Broadcasting Service began to broadcast a few programs in FM for the use of many radio factories that were in Denmark at that time. Gravenhorst was given the task to develop FM receivers that could be sent to Julius Bomholt, Director of P&T and other dignitaries so that these esteemed gentlemen could decide whether the State Radio could continue broadcasting on FM channels. In the middle of 1942 I attended Gravenhorst's first presentation of his finished product. It was on the 3rd floor of the Radio House in Rosenørns Allé. The whole chain was shown – microphone amplifier, FM transmitter, Gravenhorst's FM receiver, amplifiers and loudspeakers. It was really impressive how little noise was emitted from the loudspeakers when there was no sound from the broadcasting studio. His FM receiver was a piece of art to look at. He had laid all the circuit wires completely parallel with sharp 90° bends on a highly polished chassis.

On the same occasion, Gravenhorst also demonstrated some excellent newly bought AEG tape recorders. The Radio Broadcasting service got two of these specimens. I am quite convinced that they were a part of the German package that P. O. Pedersen got the finance ministry to buy. When these recorders arrived, they had

Figure 16. One of the AEG tape recorders acquired by the Radiohuset.

DC-bias according to the instruction manual. Some tape recorders were quickly changed to high frequency (HF) bias. However, I am not aware whether these changes were made before or after Gravenhorst's demonstration

H. C. Jørgensen (M.Sc.) who was responsible for laying down the cables and for the technical processing of the microphone signals has written a book: *Statsradiofoniens Teknik*. Here one can see that the AEG tape recorders, which Gravenhorst used for the demonstration of his FM receiver, were most likely changed from the original DC-bias to HF-bias. Diploma engineer Walther Weber at the German Radio Broadcasting service made the HF-bias discovery. There were rumors that this was made accidentally. Shortly after H. J. Braunmühl arrived, he was shown around the 'Radiohuset' by the telegraph engineer Heegaard. Braunmühl had brought along details of HF-bias, which were then built into the AEG tape recorders that the State radio owned.

In the literature, Braunmühl was said to be the designer of the Neumann recorder. I had used this fantastic instrument for recording reverberation times. I was rather impressed by the fine printout it produced on red waxed paper. The Neumann recorder had, however, the disadvantage of heavy wear on the potentiometer-drive system, which I really wanted to discuss with the designer. Since Von Braunmühl appeared in a black SS uniform with many silver decorations, I became rather uncomfortable and thought it best to held back.

I heard of a U.S.A. version of the invention of HF-bias. It was credited to a young student who was an amateur radio enthusiast interested in electronics. His thought was logical – if one thoroughly disturbed the magnetic particles coating the tape, they would settle in the right direction, whereby the S/N ratio would improve. I have not been able to confirm this, but as HF-bias became known in Germany and the U.S.A. simultaneously, both versions could be correct. S/V

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