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Contents

Front and rear cover pictures
The front and rear cover pictures (illustrating inner ear damage due to noise exposure) show photographs, taken by a scanning electron microscope, of a slide prepared from the Organ of Corti of a guinea pig. The hair cells in the upper row of the front cover picture can be seen to be undamaged. At the bottom there should normally be three rows of hair cells in a "V" arrangement. The missing hair cells in the first row as well as the missing three in the middle row are evident while the bottom row is intact.

The back cover picture illustrates (on the left) damage of the hair cells where they cling together to form large groups. The uppermost row reveals loss of two hair cells, the second row one hair cell, while the third row is intact.

We wish to thank Med. Dr. Göran Bredberg from "Akademiska Sjukhuset" in Uppsala (Sweden) for providing us with the photographs.

Do We Measure Damaging Noise Correctly?

by

Civiling., dr. tech. P. V. Brüel

ABSTRACT

Measurement and analysis of several industrial noises, for determining the risk of hearing loss due to noise, revealed significant peaks of short duration especially in the environment of the iron and steel industry. Since these peaks contain significant amount of energy in the frequency region 4 — 6 kHz and also because these frequencies are amplified in the outer and middle ear it explains why the hearing loss always starts around 4 — 6 kHz and also why the risk of hearing loss is considerably higher in this case than that given by the total noise dose criterion. Finally, a rather simple method has been proposed for setting the limits for risk criteria taking into consideration the total noise dose as well as the impulsive content of the noise.

SOMMAIRE

La mesure et l'analyse de différents bruits industriels, effectuées en vue de déterminer les risques de perte d'audition dus au bruit, mettent en évidence des pointes significatives, de courte durée, en particulier dans les industries du fer et de l'acier. Ces pointes contiennent une importante quantité d'énergie dans la partie 4 — 6 kHz du spectre de fréquence et comme ces fréquences sont amplifiées dans l'oreille externe et moyenne, ceci explique que les pertes d'audition commencent toujours autour de 4 — 6 kHz et, aussi, que le risque de perte d'audition, dans ce cas, est considérablement plus élevé que ce qu'indique le critère de la dose de bruit totale. Finalement une méthode assez simple a été proposée pour fixer les limites des critères de risque en prenant en considération la dose de bruit totale aussi bien que le contenu impulsif du bruit.

ZUSAMMENFASSUNG

Zur Bestimmung des Risikos einer Gehörschwächung durch Lärminwirkung wurden mehrere industrielle Lärmquellen gemessen und analysiert.

Es ergaben sich signifikante Spitzenwerte von kurzer Dauer, besonders in der Umgebung von Eisen- und Stahlindustrie. Diese Spitzen weisen im Frequenzbereich von 4 — 6 kHz einen bemerkenswerten Energieinhalt auf. Im äußeren — und mittleren Ohr werden diese Frequenzen zudem noch verstärkt. Das erklärt die Tatsache, warum eine Gehörschwächung immer bei 4 — 6 kHz herum beginnt, und warum das Risiko einer Gehörschwächung in diesem Fall beträchtlich höher liegt, als es durch das Kriterium der Gesamtlärmdosis angegeben wird.

Schließlich wurde eine recht einfache Methode vorgeschlagen. Bei der Festsetzung der Grenzen für die Risikokriterien soll die gesamte Lärmdosis als auch der Impulsgehalt der Lärmquelle berücksichtigt werden.

Introduction

Noise, according to a rather hackneyed expression, is characterised as undesired sound i. e. sounds that disturb, annoy and perhaps even impair hearing. It is therefore paradoxical that the internationally standardized Sound Level Meter is developed entirely on the basis of measuring sounds that we *wish* to hear without due consideration to the sounds that disturb or annoy and none at all to those (which is much worse) which involve a risk for hearing damage. When one therefore asks, *"Do we measure noise correctly?"* the answer must be that where hearing level is concerned, the scale that is in use today is applicable because the scale itself was developed originally on the basis of hearing level. If, however, one considers the annoyance caused by noise, then our noise scale is no longer completely correct and even more inappropriate when we use it to stipulate acceptable noise limits to prevent hearing loss. The latter is rather serious since large sums are being offered for prevention of hearing loss caused in industry and by traffic.

If the risk of hearing loss has to be determined for highly fluctuating industrial noise, gunshots and hammer blows, the results of readings from such a Sound Level Meter can be completely misleading. This is because the high sound impulses with significant energy content in the frequency region 4 — 6 kHz are short enough so that they are neither registered as loud sounds by our hearing mechanism nor give a significant reading on our Sound Level Meter. It is shown that a Sound Level Meter for assessing the risk of hearing loss has to be 1000 times faster than even the present day Impulse Sound Level Meter. In order to read such a fast meter indication the Sound Level Meter must contain a "Hold"circuit so that the Peak Value of short impulses can be read off.

By measuring different types of sounds and impulses with such an apparatus and comparing the results with the time constants of the outer ear, middle ear, the organ of Corti together with the integrating time of the brain, one can give clear explanations for a number of paradoxes that have been hitherto inexplicable. E. g. Why does the hearing loss start in the frequency region around 4000 Hz when the most significant components in almost all kinds of industrial noise is in the frequency region 250 — 1000 Hz? Why do teenagers visiting discothèques where the sound level is 110 — 115 dB(A) hardly ever suffer from hearing loss, while workers in industry where the sound level is 90 — 95 dB have their hearing impaired?

Finally, it has been shown that in evaluating the damaging effects of noise and thereby setting the limits for maximum permissible noise levels, not only must the sound levels be determined with a normal sound level meter but also the impulsive content of the noise must be determined with a sound level meter that has a peak holding capacity. The risk limits can then be set in several ways: in this article a rather simple method has been proposed which has a further advantage that all the material available today, from experience gained about the correlation between the measured noise and hearing loss, can be utilized by a simple correction for the content of peak values in the noise.

In the Appendix it is shown how short impulses with relatively high energy content around 4 kHz are almost always amplified by resonance in the outer and middle ear so that these impulses reach the inner ear with an amplitude 10 — 12 dB higher than other types of noise.

Sound Level Meters

a) Normal Sound Level Meter

Around 1928 Fletcher and Munson published their well known investigations of the sensitivity of the human ear to pure tones of different frequencies and intensities, see Fig. 1, [1, 2]. It must be emphasized that these investigations apply only to the hearing level of continuous pure

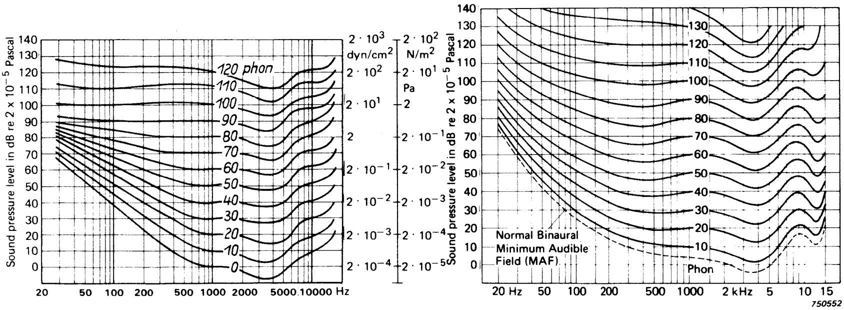

Fig. 1. Fletcher and Munson's curves of the sensitivity of the human ear to pure tones at different frequencies compared to a pure tone at 1000 Hz. Right, later measurements which form the basis for IEC standards

tones that are compared with the 1000 Hz tone. It does not take into account annoyance or the variation of loudness with time.

The weighting curves that were named A, B and C were the inverted Fletcher-Munson curves of Fig. 1 where the A curve was to be used for low level sounds, B for medium level and C for high level sounds.

The time constant was made as short as it was possible with the know-how available in those days, approximately 125 ms. The rectifier was later specified to be an RMS rectifier so that the different frequency components were added together energywise correctly.

Since the meter indication was difficult to read on account of the relatively fast deflections of the meter needle when the noise fluctuated, another meter damping position "Slow", was introduced with a time constant that was approximately 8 times as large as the one on the Fast position. The time constants "Fast" and "Slow" were chosen arbitrarily and has no relation to the preception rate of the human ear.

These were the beginnings of the present-day sound level meter that is universally used, Fig. 2. The principle is exactly the same, however, through the IEC Standardization the accuracy of the instrument has been increased by restricting different tolerances, [3]. Also the weighting curves have been modified slightly compared to Fletcher-Munson's curves for the sake of easier production while the time constants of the instrument have been specified precisely through tighter tolerances.

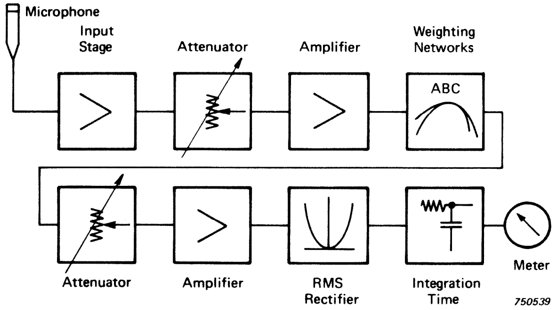

Fig. 2. Objective sound level meter consisting of a microphone, amplifier, attenuator, weighting curves A, B and C, amplifier, attenuator, rectifier, integrator and meter

In the mid-sixties it was clear that the normal sound level meter did not measure fluctuating noise appropriately, possibly because of incorrect time constants, which therefore lead to the development of the so-called Impulse Sound Level Meter.

b) Impulse Sound Level Meter
If a pure tone or noise is held constant over a long time, the human ear will perceive it with constant loudness over the corresponding period of time. If, on the other hand, the sound exists only for a short time, under 200 ms, the human ear will perceive it as less loud than it actually is, and the shorter the tone is, the weaker will it sound.

Several researchers have investigated this phenomenon closely and in Fig.3 many of their results are shown. The ordinate shows how much larger the physical strength of the pertinent short duration impulse must be than the same sound of longer duration, for it to sound equally loud.

From the figure it can be seen that there is a considerable spread in the results. However, it has been agreed upon by IEC to choose 35 ms as the averaging time for Impulse Sound Level Meter corresponding to the fully drawn curve shown in Fig.3.

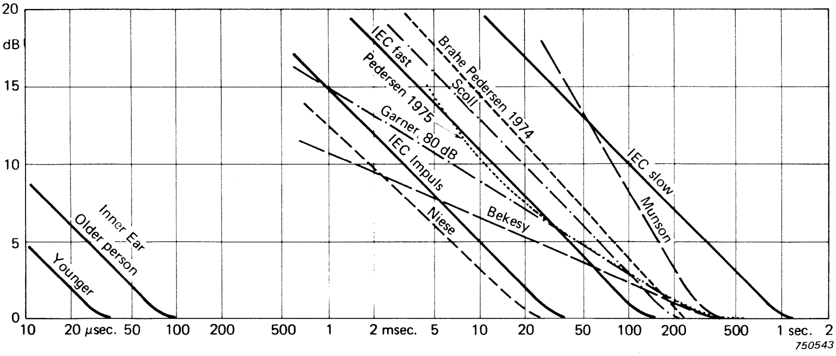

Fig.3. Results from different researchers of the subjective perception of short impulses compared with the integration curves for time constants "Fast", "Slow" and "Impulse" of the sound level meter. On the extreme left the integration curves of the human ear, for the young and the elderly respectively which are approximately 1000 times faster than the impulse curve of the sound level meter

For all the measurements that have been referred to and shown in Fig.3 the hearing level i.e. subjective loudness of the corresponding sound impulses has been used as the basis. The curves do not give an insight into the degree of annoyance caused by different impulses and they cannot at all be used for predicting the damaging effects of sound impulses on the human ear. It should be emphasized that many people believe that the IEC standardized Impulse Sound Level Meter can be used to set acceptable noise limits that will avoid the damaging effects of noise.

It is commonly accepted that the averaging time of the ear which is defined to be 35 ms is the same for both increasing and decreasing levels of noise. This may be correct, though it has never been proved. Nevertheless, for the Impulse Sound Level Meter the time constant has been completely arbitrarily chosen to be 3 s for decreasing levels i.e. 100 times longer than for increasing levels, [4]. The long time constant of 3 s for decreasing levels has been introduced strictly from a practical point of view in order to be able to read-off the meter when single impulses are measured. This long time constant is similarly in no way related to the hearing mechanism and it is more than doubtful if repetitive pulses can even remotely be measured correctly, whereas the response to a single impulse will generally correspond to its subjective loudness.

On the extreme left of Fig.3 the integration curves of the *inner* ear for the young and the elderly are shown which are approximately 1000 times faster than the impulse curve of the sound level meter.

Measurement Results

It has been known for more than 40 years that hearing loss always starts around 4 — 6 kHz (C_5-dip), and as a rule it is most severe at 6 kHz, independent of whether the damage has been caused by a single shot, firework, small explosion or similar singular events, or if the loss has occurred gradually due to long term exposure in a noisy environment. The latter is very strange, since practically all the industrial noise we know has a higher intensity in the frequency range 250 — 500 Hz than at 6 kHz. There has been considerable speculation as to why hearing loss due to industrial noise occurs 3 octaves higher on the frequency scale than the corresponding frequency region with the most energy content, and no sensible explanation has been given to date.

Figs.4 and 5 show some typical audiograms of industrial workers with hearing loss who have been exposed to different noise levels for long durations. Also shown with the audiograms are the corresponding typical spectrograms of the noise that the worker has been exposed to.

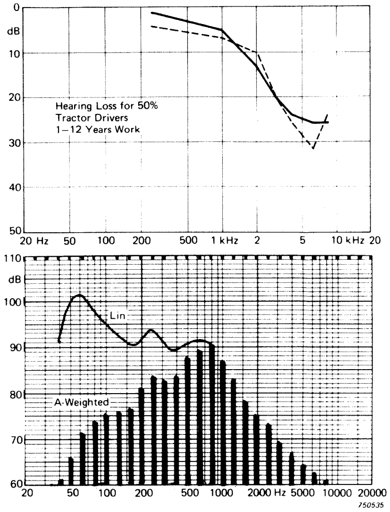

Fig. 4. *Average audiograms of tractor drivers after approximately 10 years of work. Bottom, frequency spectrum of tractor noise, both linear and A weighted. Figures represent sound pressure levels in 1/3 octaves. (Hansson & Kylin)*

If the noise is uniform without excessive impulses (e.g. in a carpentry workshop) it can be shown that the human ear damage is related to the total noise dose the worker has been exposed to in his lifetime. The percentage risk can be expressed by a formula where the equivalent noise level for each working day is added over the number of years of exposure to the corresponding noise, [5]. Also for fluctuating noise levels e.g. in the case of a tractor driver that drives in and out of a factory, it seems that the risk of hearing loss is related to the total noise dose over the years [6, 7]. However, this is not the case when the noise contains short impulses e.g. noise from punch presses, riveting machines, plate straightening machines, hammer blows, pneumatic nailing machines etc. For these cases, the risk of hearing loss appears to be significantly higher than that according to the total noise dose. Depending on how impulsive the noise is, one must correct it by 13 — 20 dB, [8, 9].

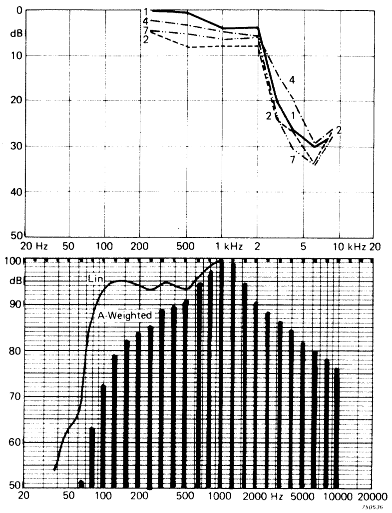

Fig.5. Audiograms of a group of Swedish forest workers who have felled trees with chain saws for 1, 4, 7, 10 and more than 12 years respectively. Bottom — typical spectrogram and 1/3 octave sound pressure levels of the corresponding chain saw noise. (Hansson, Kylin and Gustavsson)

The situation is quite the opposite in the case of permanent ear damage caused by gunshots and clicks. Very loud noise, even of short duration can rupture some of the fine hair cells which are activated by the Basilar membrane, whereby they become inactive either temporarily or permanently depending upon the intensity of the noise. This kind of ear damage is completely different to that due to steady noise where the product of intensity times time i. e. the total noise dose, causes damage by a fatigue phenomenon.

Fig.6 shows a measuring arrangement where the pistol shot via 1/4" microphone is amplified by the Sound Level Meter Type 2209 and captured by a Digital Event Recorder Type 7502 which is ideal for storing and playing back the signal at a faster rate. Most of the shots have been recorded after they have been A weighted since it gives a truer representation of the loading on the inner ear. By repeating the signal with the aid of the Digital Event Recorder, the sound pressure of the pistol shot can be displayed on an oscilloscope as a function of time. The frequency content of the signal is obtained using the Real Time Analyzer Type 3347.

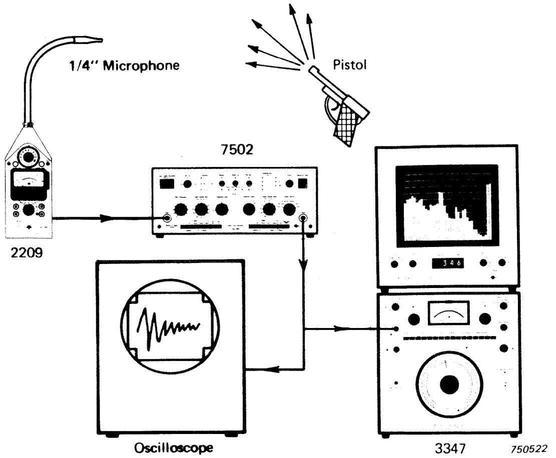

Fig. 6. Measuring arrangement for obtaining oscillograms and frequency analyses of short impulses

Fig. 7 shows an audiogram taken on a person that had been exposed to a gunshot while Figs. 8 and 9 show some oscillograms and spectrograms of shots from a signal pistol a toy pistol and a clicking noise from a toy monkey.

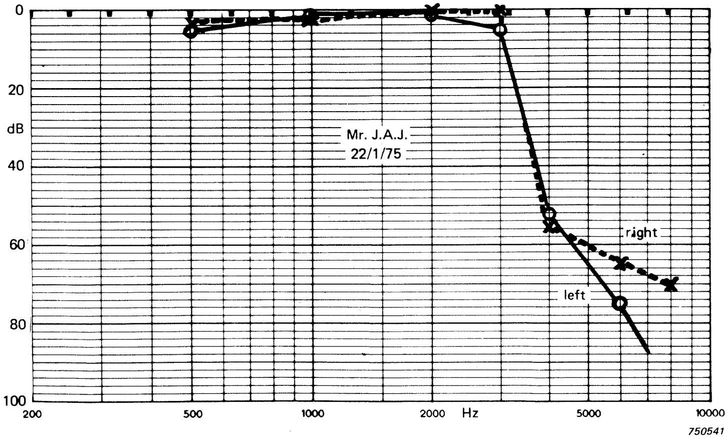

Fig. 7. Typical audiogram illustrating hearing loss of a person who has been exposed to a gunshot

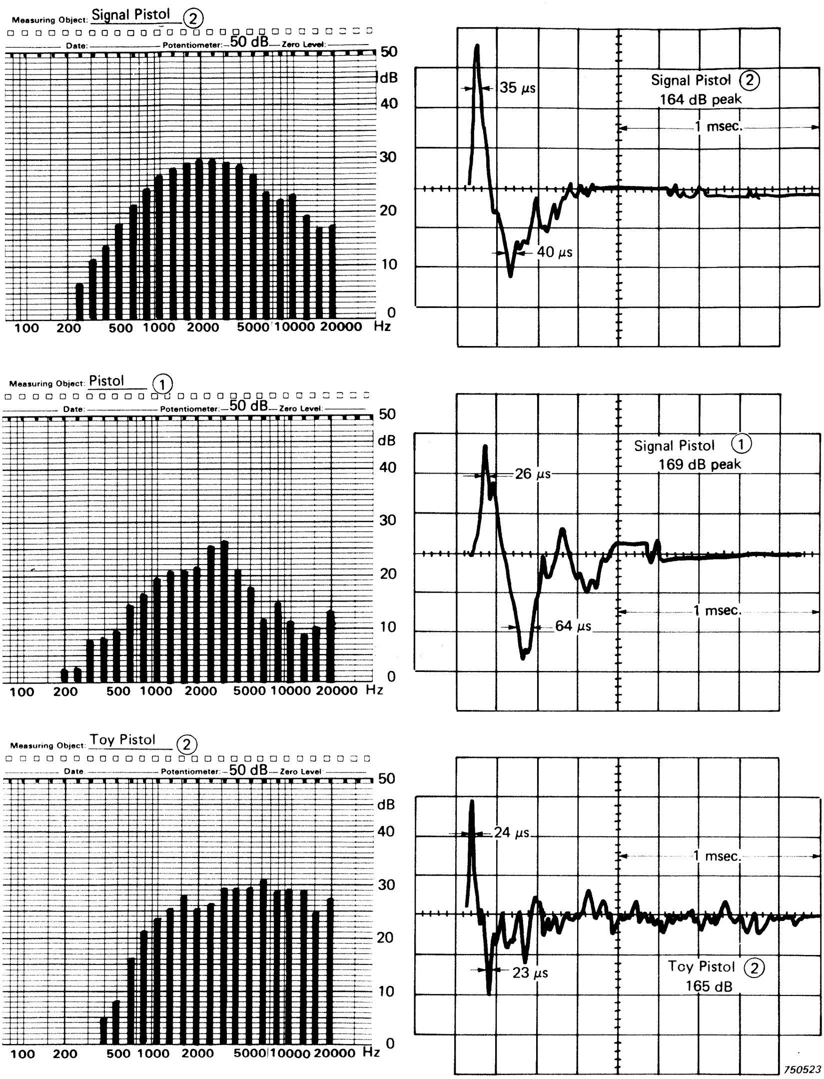

Fig. 8. *Spectrograms and oscillograms of a shot from a signal pistol at*
a) 0,5 m distance
b) 1 m distance
c) shot from a toy pistol with cap at 10 cm distance

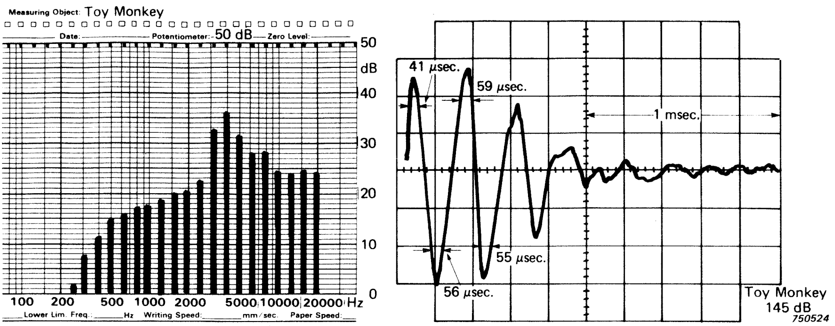

Fig. 9. Clicking noise from a toy monkey. Periodic at 4000 Hz. 145 dB "Peak"

The analyses of these sounds show that the maximum energy content lies in the frequency region 4 — 6 kHz. On account of the short duration of the pistol shots, the result from a normal sound level meter would only give an expression of the energy content of the shot. It does not give any information of the high instantaneous values for which a special sound level meter with "Peak Hold" is required. Further, it can be seen that the signal almost always consisted of one or more whole periods with equal positive and negative pressure peaks, in contrast to what was previously assumed that an impulse was a short, high-level, positive pressure peak followed by a long, negative pressure pulse with much lower amplitude. It is therefore quite natural that the ear is most affected and damaged around 4 kHz by the response of a gunshot, an impulse or a click. This naturally leads to the investigation of industrial noise whether it contains the short, high sound impulses with significant energy content in the frequency region 4 — 6 kHz, but short enough so that they are neither registered as loud sounds by our hearing mechanism nor give a significant reading on a normal sound level meter.

Figs. 10, 11 and 12 show oscillograms and spectrograms of a hammer blow on a hard material, impact between two bottles, and the sound generated during perforation of a plate by a punch press respectively.

Analyses of these industrial noises reveal significantly high level sound impulses with both positive and negative pressure amplitudes — usually sequences of some milliseconds with large energy content in the frequency region 2000 — 5000 Hz with maximum peaks 15 — 25 dB

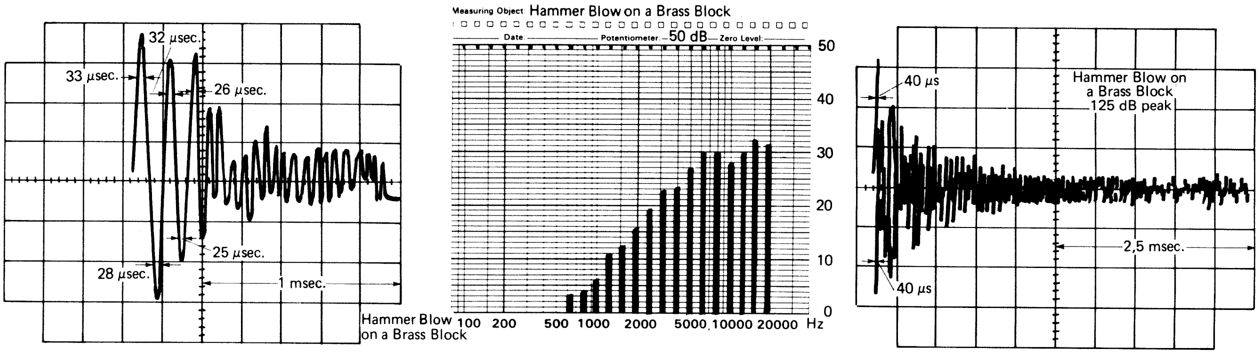

Fig. 10. Hammer blow on a brass block

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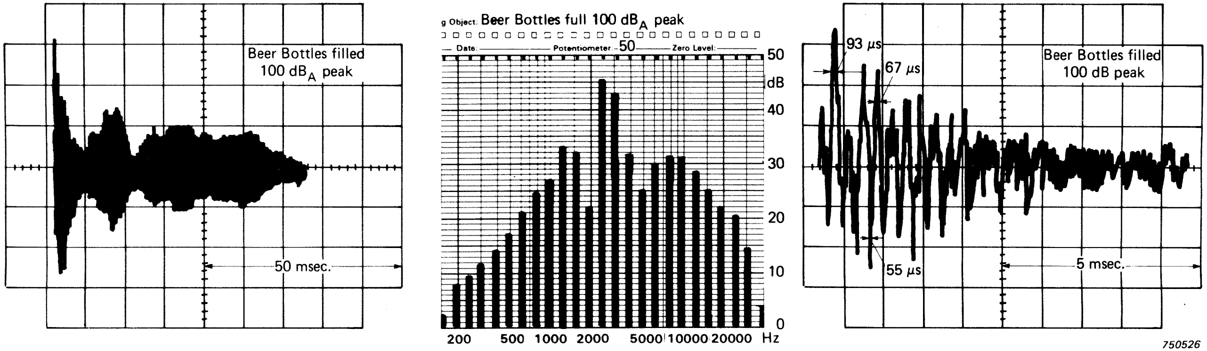

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Fig. 11. Noise from impact between two bottles

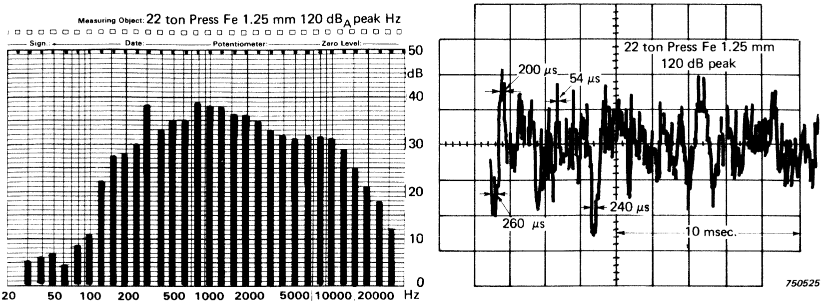


Fig. 12. Sound during perforation of a plate by a Punch Press

higher than the mean value measured with a normal sound level meter. Also the maximum pressure durations are between 30 and 200 µs.

Since we do not even remotely preceive the loudness of the short sound impulses correctly, one could ask: How can the ear be damaged by these impulses which sound so weak? Before the question can be answered, it is necessary to describe the ear, its integration times and the transmission characteristics of the different parts of the ear.

The Ear and Its Integration Time

Fig. 13 shows a schematic drawing of the human auditory system. The drawing is rather unorthodox as emphasis is placed on accentuating the elements and characteristics that have special significance seen from a communication technologist's viewpoint.

The lever-arm mechanism is sketched with only a single lever-arm. Such a transmission system with stiffnesses (of ear drum and Oval Window) masses and moments of inertia (of lever-arm and membranes) together with friction (mostly from the inner ear) do not transmit all frequencies equally well. The stiffnesses impede the transmission characteristics of low frequencies and inertia the higher frequencies; the transmission is best at resonance (approximately 1200 Hz). Since friction contributes to the major part of the impedance, the resonance is not particularly sharp and transmission is good between 500 — 8000 Hz. [10, 11]. The shape of the outer ear with the auditory muscle and ear canal has also a resonance amplification on account of the shape of both the head and the auditory muscle and especially the ear canal which gives a quarter wavelengths amplification around 4 kHz. [12]. Neither is this resonance particularly sharp.

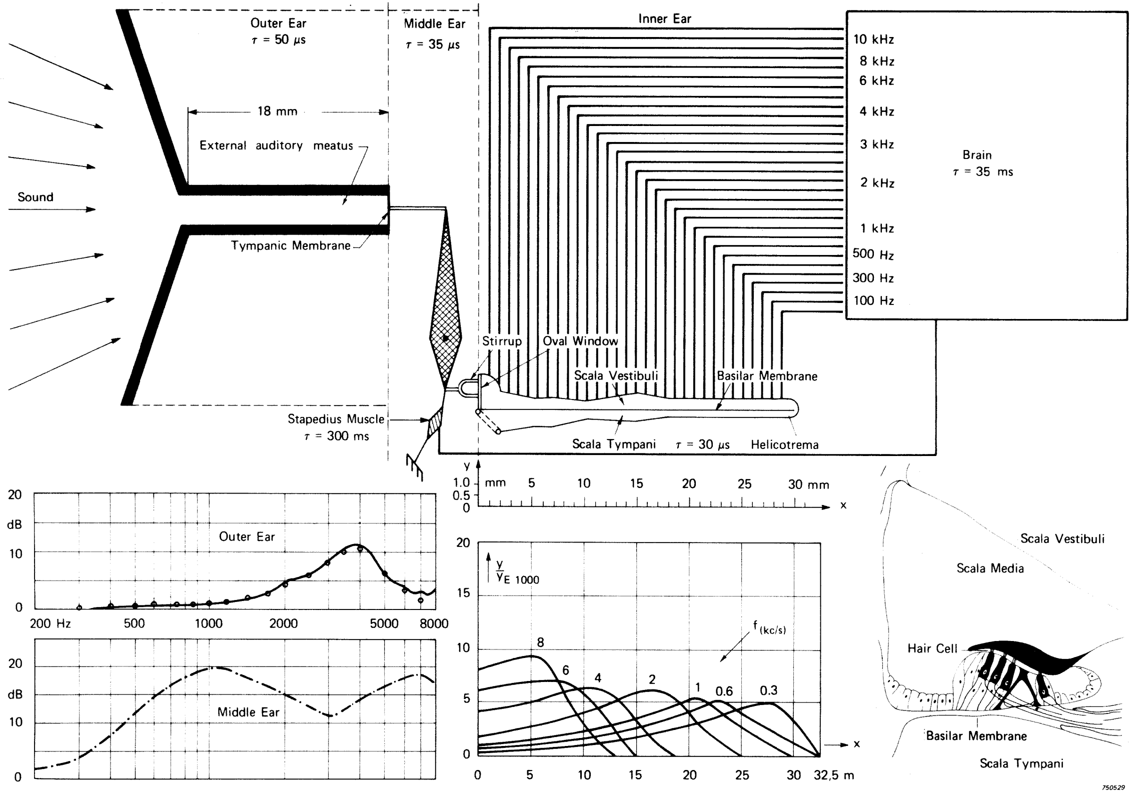


Fig. 13. Schematic drawing of the human ear with the teletransmission system's most important time constants, frequency curves, vortex curves, frequency positions and integration constants

It has already been shown that the brain which perceives the hearing impression has an averaging time between 20 — 100 ms (Fig.3) with a defined mean value of 35 ms. These are very long times and completely incompatible with the capability of detecting frequencies above 20 — 50 Hz, if it was the brain that should carry out the frequency analysis. If the brain were to perceive and analyze frequencies around 15 — 20 kHz then the averaging times should be correspondingly lower i. e. shorter than 50 — 100 μs. The reason why the brain perceives frequencies over 50 Hz is exclusively due to the major part of the frequency analysis already being carried out in the *inner* ear and transmitted to different parts of the brain through parallel nerve fibres, completely analogous to the principle used in modern real time analyzers. On the other hand, since the inner ear receives all the frequencies simultaneously at its input terminal and is able to handle and distinguish all the amplitude variations so rapidly, the averaging times must therefore be considerably shorter. From the frequency curves of the ear shown in Fig. 1, the relevant averaging times can be found by determining the upper cut-off frequency.

In telecommunications the upper cut-off frequency is defined as the frequency where the amplification has fallen by 3 dB. From Fig. 1 and also the A weighting curve which is the inverse of the hearing sensitivity curves (Fig. 1) the averaging time of the inner ear can be stipulated to be 30 μs for normal cases and 100 μs for the elderly, who can no longer hear the higher frequencies well, see Fig.3.

As mentioned above, the middle ear and the outer ear incorporate frequency dependent transmission response curves with resonant frequencies at 1000 and 4000 Hz respectively with their corresponding time constants. Since the transmission response curves are rather flat, they contribute only as a correction factor to the short averaging times of the inner ear. On the other hand, the muscle contractions in the middle ear have significant importance. These muscles are activated around 75 — 90 dB(A) reducing the sensitivity of the ear at low frequencies. However, this does not occur instantaneously, since it takes time for the signal to pass from the muscle, ear and nerves to the brain where it is perceived and sent back to the muscle. The total time is approximately 300 — 500 ms. [13].

Discussion of Results

Having examined the transmission characteristics of the different parts of the ear, it can be seen that the short impulses are transmitted without obstruction through both the outer and the middle ear to the nerves in the organ of Corti, where the nerve ends are exposed to the full amplitude also of the short sound impulses; it is first the summing up in the brain of the sound impression that perceives a short impulse as less loud than a longer one.

It is further shown that there is a resonance amplification of 3 — 10 dB in the outer and middle ear of frequencies around 4 kHz. It is therefore quite natural that the damaging effects of also the industrial noise on our hearing faculty starts in the frequency region around 4 kHz, partly because by far the majority of the high noise levels are to be found in this frequency region (although we cannot hear them with their proper loudness) and partly because of the resonance of the ear at 4 kHz which further amplifies periodic sound pressures with a frequency of 4 kHz.

It can be concluded from the analyses of the impulses shown that we are exposed daily to impulsive noises which are more intensive than our hearing impression perceives them to be. However, these impulses are so long that they reach the inner ear with their full amplitude. It has been shown that a short impulse that is propagated through our outer ear can be 6 — 7 dB higher at the ear drum than the highest sound pressure outside the ear, see Appendix. During passage through the middle ear, a further similar amplification can occur, so that signals with a frequency content of 4 to 6 kHz would reach the inner ear with a total amplification up to 10 — 12 dB. If the amplitude of the impulses are high enough, the nerve ends are damaged, even though a normal sound level meter would indicate that the noise is lower than the danger level.

Risk Criteria

The consequence of our finding this reasonable explanation of the mystery of the hearing threshold shift at 4 kHz is that in evaluating the damaging effects of noise and thereby setting the limits for maximum permissible noise levels, we must not only determine the sound level with a normal sound level meter, but must furthermore determine the impulsive content of the noise with a sound level meter that can be charged up very quickly. This evaluation can be carried out in several ways: in the following, a rather simple method has been proposed which has the further advantage that all the material available today, from experience gained about the correlation between the measured noise and hearing loss, can be utilized by a simple correction for the content of peak values in the noise.

A number of measurements have been taken in different industries with the use of a B & K Sound Level Meter Type 2209 with "Hold" circuit for peak voltage measurements and which, with the A-filter coupled in, has an averaging time of 30 μs for peak measurements. The sound level meter was equipped with a 1/2" microphone for some of the measurements while a 1/4" microphone was used for both high levels and the sharpest peaks.

The results are shown in Table 1. The measurements were all taken according to dB(A) "Fast"(125 ms), dB(A) "Impulse"(35 ms), and dB(A) "Imp. Hold" in which case the reading noted was the mean of 5 values measured with approximately 10 second intervals. Finally, measurements were also taken with dB(A) "Peak Hold"(30 μs) with 5 to 10 second intervals and the mean of 5 measured values noted. The most interesting aspect in this connection is to ascertain how large the "Peak" value is above dB(A) "Fast" or dB(A) "Impulse" and is denoted by Δ in the table. The larger the difference is, the more dangerous the noise. A pure sinusoidal tone has the same value for "Fast" and "Imp. Hold" while the "Peak" value should be and is 3 dB higher. It can be seen that beat music and other electronic music has very low peak values; the same is true for noise in aircraft and a number of (especially high speed) machine tools and woodworking machines. Larger differences are revealed by lawn mowers, type writers, and naturally all types of percussion machines such as pneumatic nailing machines, bottling machines (bottles clattering against each other) and punch presses. Obviously direct impacts, gunshots and explosions manifest the largest differences.

It is now possible — from the theories developed here, together with the vast amount of practical experiences described in literature — to set-up some risk criteria for different types of industrial noise.

Passchier-Vermeer has in the reference mentioned earlier, [9], directly related the hearing loss to the L_{eq} measured in three different branches of industry:

a) wood industry with relatively steady noise,

b) metal industry with percussion machines, lathes and milling machines,

c) metal industry with punch presses,

the last two with fluctuating noise. Since the hearing loss in the wood industry relates reasonably well to the total energy principle, there is every indication that it is correct for noise without peaks. On the other hand, the figures for the metal industries do not agree well, as hearing loss occurred at equivalent noise levels that were 10 — 20 dB lower than the noise in the wood industry.

Passchier-Vermeer has put forward a criterion for hearing loss in the wood industry and other constant level noise, which gives a 50% probability for hearing loss after 10 years of normal days work in an equivalent noise level of 102 dB. From here, one can set-up risk criteria for other types of noise with different relations between their peak and dB(A) values. By comparing the results given in Table 1 for machines in the wood industry and other machines with constant noise levels, it can be seen that the peak values are around 10 dB higher than the dB(A) values for this type of noise. As a result, the base line after the total energy principle, valid for 3 months to 20 years of noise exposure, is drawn 10 dB above the line for wood-working machines in Fig. 14.

By referring to Table 1 and finding the difference between the peak value and the dB(A) value, the risk criteria for different types of noise

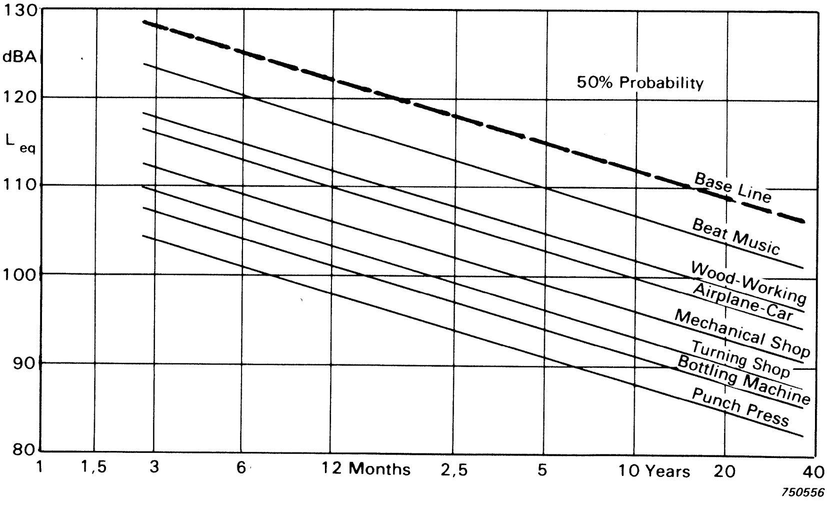


Fig. 14. Risk limits of hearing loss (50% probability) for different types of noise, evaluated on the basis of the relation between dB(A) value and Peak value

Sound Source	**Fast dB(A)**	**Imp. dB(A)**	**Imp. Hold dB(A) 5 x**	**Peak Hold dB(A) 5 x**	**Δ**
Sinusoidal pure tone 1000 Hz	94	94	94	97	3
Beat Music from a grammophone	90	91	93	97	4
Modern music from a grammophone	102	103	103	105	2
Electric guitar from a grammophone	85	86	86	91	5
Motorway traffic 15 m distance	80	80	81	89	8
Motorway traffic 50 m distance	68	68	68	76	8
Train 70 km/h rail noise 10 m distance	95	96	98	106	8
Train 70 km/h rail noise 18 m distance	85	87	87	94	7
Noise in aircraft Type PA 23, cruising speed	90	91	91	100	9
Noise in aircraft Type Falco F 8, cruising speed	97	98	98	109	11
Noise in aircraft Type KZ 3, cruising speed	102	102	103	112	9
Noise in car Type Fiat 500, 60 km/h	78	79	79	93	14
Noise in car Type Volvo 142, 80 km/h	75	75	76	86	10
Lawn mower 10 HK 1 m distance	97	99	99	116	17
Typewriter IBM (Head position)	80	84	83	102	19
Electric shaver 2,5 m distance	92	92	92	107	15
75 HK diesel motor in electricity generating plant	100	101	101	113	12
Pneumatic nailing machine 3 m distance	112	114	113	128	15
Pneumatic nailing machine near operator's head	116	120	120	148	28
Industrial ventilator 5 HK 1 m	82	83	83	93	10
Air compressor room	92	92	92	104	12
Large machine shop	81	82	82	98	16
Turner shop	79	80	81	100	19
Automatic turner shop	79	80	80	99	19
40 tons Punch press, near operator's head	93	98	97	121	24
Small automatic Punch press	100	103	103	118	15
Numerically driven high speed drill	100	102	103	112	9
Small high speed drill	98	101	101	109	8
Ventilator with filter	82	83	83	94	11
Machine driven saw, near operator's head	102	102	104	113	9
Vacuum cleaner Type Hoover, 1,2 m distance	81	81	81	93	12
Bottles striking each other	85	88	90	105	15
Bottling machine in brewery	98	99	101	122	21
Toy pistol (cap)	105	108	108	140	32
Pistol 9 mm, 5 m distance from side	113	114	116	146	30
Shotgun 5 m distance from side	108	110	111	143	32
Saloon rifle 1 m distance from side	107	110	110	139	29

Table 1.

such as from punch presses, in turning shops, mechanical workshops, noise in aircraft etc. can be found. It can be seen from Fig. 14 that KZ 3 aircraft, mentioned in Table 1, could be flown approximately 7 years with a 50% probability of hearing loss, whereas beat music with a noise level of 115 dB(A) could be endured for approximately 18 months of total noise exposure.

The curves shown in Fig. 14 are taken from the measurement results given in Table 1. When faced with a practical problem, it is best to measure the difference between the peak value and dB(A) value of the corresponding noise. The risk criterion can then be drawn relative to the base line and parallel to it.

The difference between the peak value and dB(A) value should be determined over a long time and in various places. Also, in evaluating the risk criterion the mean value should not be taken directly but, to be on the safer side, rather more weight should be placed on the highest levels.

In the risk criteria given in Fig.14 the levels of the very short noise peaks contribute their full value. It might rightly be argued whether this is correct. It might be possible to think of a combination where the peak values contribute only half or two thirds of their dB values to the risk criterion. To determine this requires more measurements and practical information than we have today.

On the other hand, Passchier-Vermeer has found, for the two metal industries that she has investigated, that punch press plants should have approximately 13 — 17 dB lower noise levels than the wood industry for the same risk. For the measurements taken here on punch presses, a difference of 14 dB is found. For a normal mechanical workshop with a combination of percussion machines, drilling and milling machines, Passchier-Vermeer has found a difference of approximately 9 dB, while for this investigation 6 dB was found for a normal mechanical workshop and 9 dB for a turning shop. This information indicates that the peaks should contribute to the risk criteria with their full value.

It has to be stressed that it is only in "normal" industrial noise that these risk criteria can be valid. As soon as there is an exceptionally long time between these peaks, like single shots and punch presses which are only used very seldom, these risk criteria cannot be used directly.

Conclusion

It is well known that for industrial noise the limits for the risk of commencement of the hearing loss is 85 — 90 dB(A) while 100 dB(A) presents an extremely high risk even after a relatively short time. One therefore cannot help wondering why youngsters, who go dancing day after day in discothèques where the noise levels from beat music is often 110 — 115 dB(A) do not, according to all available investigations, differentiate themselves from reference groups of the same age, [14]. Many have noticed this phenomenon and different explanations have been searched for, e. g. movement of the body should reduce the risk of hearing damage, [15].

Another example is some flying instructors who have for more than 5000 hours flown a very noisy training aircraft of the type KZ 3. They have always flown without radio and without ear-protectors. Yet their hearing ability is normal in spite of the noise level of 103 dB(A) in the cockpit. Their audiograms show no deviation from the normal age-related hearing loss in spite of the many hours spent in high noise levels. On the other hand, it is well known that pilots who have flown noisy planes and used radio for communications, without special equipment for shielding the cockpit noise, often have appreciable hearing loss.

According to Table 1, both beat music and the noise in aircraft referred to, have relatively very low ratios of peak to dB(A) values. In the case of beat music, this is due exclusively to the use of electronic amplification which is limited in its capacity to deal with high peak values. The peaks are simply cut-off in the amplifier system. The noise in training aircraft is by nature very steady and continuous. The peaks due to combustion in the engines are effectively smoothed out by a small exhaust muffler, while the engine's elastic suspension takes care that the peaks are not transmitted to the aircraft body. On the other hand, the noise from radio communication systems, apart from blaring and clicks, contains many short duration high level peaks.

Another situation that is also quite inexplicable is the wide spread in the degree of hearing loss among a group of subjects who have been exposed to apparently the same noise. The variations are considerably larger than in a group of subjects who have been exposed to other types of hazards such as over-exertion, hunger, cold, weightlessness, etc. The spread in the variations for hearing loss is approximately 10 times greater.

Also, as mentioned previously, no sensible reason has been given to date why the hearing loss of industry workers due to noise is always greatest and starts around 4 kHz when the largest amount of energy in industrial noise lies in the much lower frequency region.

A possible explanation of these paradoxes and peculiarities would seem to be, that it is the noise peaks of short duration which damage the ear to a significant degree and which reach the nerve ends near the Basilar membrane but are not perceived by the brain. If this theory is accepted, we have an immediate explanation for the following:

a) that industries with steady noise are less liable to cause hearing loss than metal industries where short, high peaks are prevalent;

b) that the greatest damage occurs around 4000 Hz simply because the maximum energy content of the peaks lies in this frequency region;

c) that the wide spread in the degree of hearing loss is due to the large differences in the distribution of peaks from one working place to another. On account of the high frequency nature of noise peaks they do not propagate far, as they are damped out by air absorption. Further, objects and screens (similar to the case of light) shade large areas against noise peaks, while the noise level that is measured by a normal sound level meter is almost constant over the whole room;

d) that beat music and the above mentioned noise in training aircraft are not harmful on account of the absence of peaks.

If we take the consequences and accept that a sound level meter, developed solely to measure hearing levels, cannot be used to grade the annoyance effects and even less the damaging effects, and also accept that the short peaks in loud noise have a considerable influence on the degree of risk, we must conclude that two different sound level meters are required for measuring noise correctly:

1) a normal sound level meter to measure hearing levels, i. e. sounds that we *wish* to hear and

2) a sound level meter with a "peak"holding capacity for determining the risk of hearing loss.

References

1) Fletcher and Munson: *"Loudness, its Definition, Measurement and Calculation".* J.A.S.A. Vol. 5. 1932, p. 82.

2) Churcher and King: *"The Performance of Noise Meters in Terms of Primary Standard". J. Inst. Electr. Eng. London, 1937. p. 57.*

3) IEC: "Recommendations for Precision Sound

Level Meters". Publication 179. Geneve 1965 & 1973.

4) IEC: *"Recommendations for Impulse Sound Level Meters".* Publication 179A. Geneve 1973.

5) Robinson, D. W.: *"Estimating the Risk of Hearing Loss due to Exposure to Continuous Noise".* Occupational Hearing Loss. British Acoustical Society. Special Volume No. 1. London 1971, p. 43.

6) Hansson, Kylin and Gustavsson: *"Skogstraktorn som Arbetsplats".* Research Notes No. 32. Royal College of Forestry. Sweden 1967.

7) Kylin, B.: *"Hälso- og Miljöundersökning bland Skogsarbetere".* Research Notes No. 5. National Institute of Occupational Health, Stockholm 1968.

8) Passchier-Vermeer, W.: *"Hearing Loss due to Steady-state Broadband Noise".* Report 35. Inst. for Public Health Engineering. TNO. Netherland 1968.

9) Passchier-Vermeer, W.: *"Steady-state and Fluctuating Noise. Its Effects on the Hearing of People".* Occupational Hearing Loss. British Acoustical Society. Special Volume No. 1. London 1971, p. 15.

10) Møller, A. R.: *"An Experimental Study of the Acoustic Impedance of the Middle Ear and its Transmission Properties".* Acta Oto-Laryngol. Vol. 60. 1965, p. 129.

11) Wilson and Johnstone: *"Basilar Membrane and Middle Ear Vibration in Guinea Pigs Measured by Capacitive Probe".* J.A.S.A. Vol. 57, No. 3. 1975, p. 705.

12) Wiener and Ross: *"The Distribution in the Auditory Canal in a Progressive Sound Field".* J.A.S.A. Vol. 18. 1946, p. 401.

13) Møller, A. R.: *"Effect of Tympanic Muscle Activity on Movement of the Eardrum, Acoustic Impedance and Cochlear Microphonics".* Acta Oto-Laryngol. Vol. 58. 1965, p. 525.

14) Ewertsen, H.: *"Beat Music and Damage to Hearing"* (In Danish). Ugeskr. Læg. Vol. 133. 1971, p. 959.

15) Whittle and Robinson: *"Discothèques and Pop Music as a Source of Noise-induced Hearing Loss".* NPL Acoustic Rep. Ac 66. 1974.

16) Coles, Garinther, Hodge and Rice: *"Hazardous Exposure to Impulse Noise".* J.A.S.A. Vol. 43. No. 2. 1968, p. 336.

APPENDIX

Sound Impulses through a resonant circuit

In order to obtain an idea of how sound impulses — long as well as short — are amplified and distorted during the passage through the outer and middle ear, the following measurement results are shown.

The outer ear has a fundamental resonance around 3500 — 4000 Hz as shown in Fig. 13 on account of the resonance in the ear canal. It is a simple mechanical vibratory system, where the air in the ear canal constitutes the mass while the air volume and the ear drum constitute the spring, see Fig. 1A. The system is rather damped on account of the friction between the moving air and hair and skin. The maximum pressure amplification is approximately 4,5 times (Q = 4,5) or 13 dB at resonant frequency.

The fundamental resonant frequency of the middle ear is significantly lower, 800 — 1000 Hz and simultaneously the vibratory system is much more complicated since there are several resonances, as also

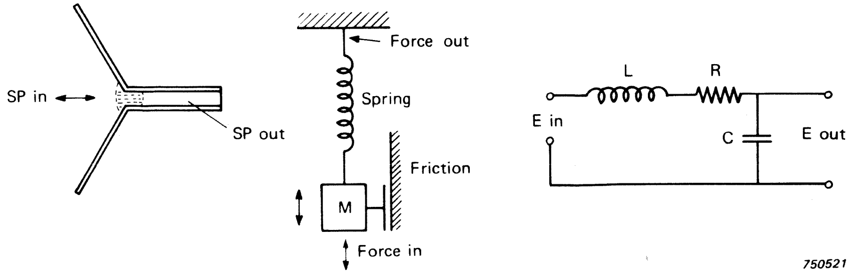


Fig. 1A. An acoustical, mechanical and an electrical simple vibratory systems
Left: Resonant circuit corresponding to the outer ear
Middle: A very simplified mechanical analogue of the lowest resonant mode of vibration of the middle ear
Right: The electrical analogue

shown in Fig.13. The masses in the vibratory system are the moving part of the ear drum, the small sound transmission bone and the oval window. The stiffness is contributed partly by the ear drum stiffness, partly by the bending stiffness of the bones and the elasticity of all the linking elements. Damping is due to the frictional resistance in linking elements together with a significant amount due to good impedance matching with the inner ear. The fundamental resonance, similar to the outer ear, gives an amplification of 4,5 times (Q = 4,5) or 13 dB. Amplification is here defined as the ratio of the pressure at the entrance of the inner ear (oval window) to the pressure at the ear drum, although it should be remembered that it is the particle velocity at the oval window that is responsible for generating the vortices in the Scala Vestibuli and Scala Tympani.

Both the outer and middle ear's vibratory system can be made analogous to a simple electrical oscillatory circuit, where the self induction L corresponds to the masses, capacitor C to the stiffnesses and the resistance R to the dampings. On such an electrical oscillatory system, some measurements of the amplification due to some typical sound impulses have been made and are shown in the following. But first of all, the normal frequency characteristics, i.e. output voltage relative to input voltage for varying frequency, have been obtained.

Fig.2A shows on the left an oscillogram with linear amplitude. The resonant frequency is 1000 Hz and the maximum voltage amplification is of

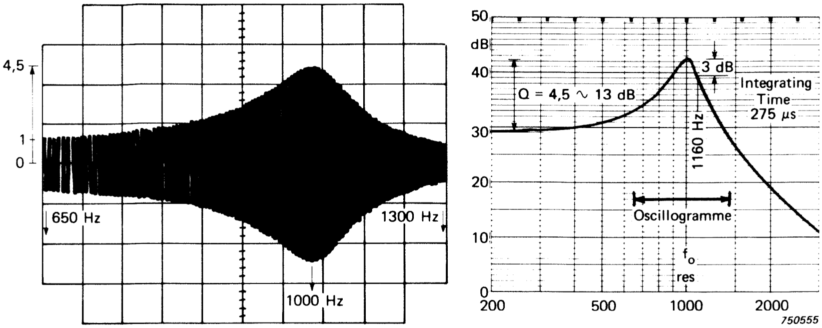


Fig.2A. Left: Resonance curve in the time domain seen on an oscilloscope for sweeping frequency
Right: Normal frequency characteristics in dB after rectification of the signal

the same order as it is for the mechanical vibratory system in both the outer and middle ear, namely Q = 4,5 or 13 dB. On the right is shown the conventional way of describing a resonance circuit, by the frequency characteristics where the amplitude is plotted on a logarithmic scale in dB against frequency. The averaging time can be determined from the upper cut-off frequency 3 dB below the top. Signals

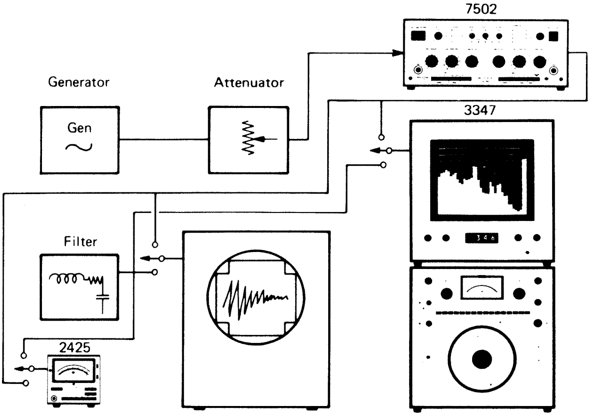


Fig.3A. Measuring arrangement with the Digital Event Recorder Type 7502 for generating any type of signal and obtaining its oscillogram, spectrogram and peak value

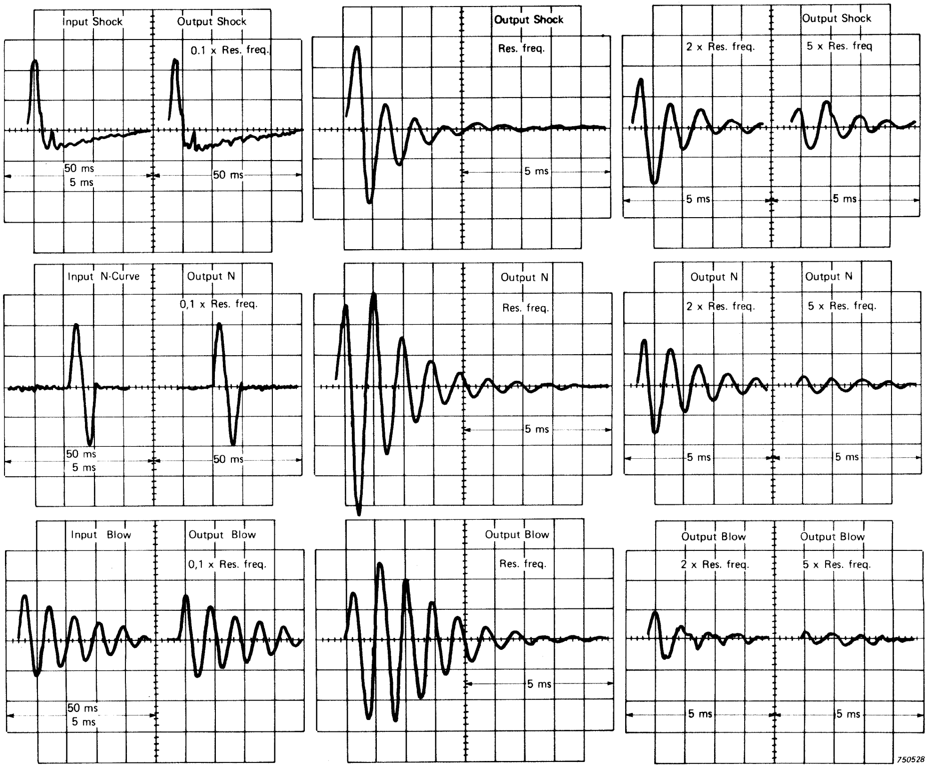


Fig. 4A. Oscillograms of an ideal gunshot, N-curve and a hammer blow before and after passing through a filter (Q = 4,5) at 0,1 times the resonant frequency, at resonant frequency and 2 and 5 times the resonant frequency that are slow (i. e. composed of low frequencies) pass through the filter without distortion, whereas faster signals are distorted. The output signals, for short impulse inputs, are proportional to the energy content of the impulse i. e. the integral of the energy in the impulse. Around resonance itself, the situation is rather complex when short impulses are applied at the input. In most cases, one obtains a pressure — or voltage — amplification of the signal and at the same time the signal is considerably distorted.

With the help of the Digital Event Recorder Type 7502 it is possible to generate any kind of a signal and play it back at any desired speed and repetition frequency. The measuring set-up shown in Fig.3A can produce oscillograms and also measure the maximum amplitude of both the input and output signals of the filter.

Three different types of impulse configurations are shown in Fig.4A. First a shock-impulse in the form of an idealized gunshot corresponding approximately to that of Coles et al. [16], i. e. a sharp, high positive pressure peak followed by a long, low negative peak. On the top of the figure on the left, the time trace of the impulse is shown and just beside it the time trace of the signal at the output of the oscillatory circuit when the signal passes slowly through it. The positive part of the pulse corresponds to 0,1 times the resonant frequency of the circuit and it can be seen that the impulse in this case goes through undistorted without any change of amplitude.

When the impulse becomes so short, that the positive part of the impulse corresponds exactly to the resonant frequency of the circuit, the situation is rather different. In this case some amplification takes place followed by a negative peak, which is just as large, and some decaying periods of oscillations. The amplification here is 23% and can theoretically reach up to 70% for an oscillatory circuit with a high Q. Frequency distortion and amplification can be seen clearly also in the spectrograms in Fig.5A, where the high frequencies of the input impulse are cut out.

If the impulse becomes even shorter, e. g. corresponding to 2 and 5 times the resonant frequency, the maximum amplitude gets smaller and smaller depending on the energy content of the impulse. The idealized gunshot impulse is of mostly theoretical interest, since, as shown earlier, it is seldom found in practice. On the other hand, the next impulse, composing of a single sinusoidal period, is experienced very often in connection with all sound phenomena, arising due to the me-

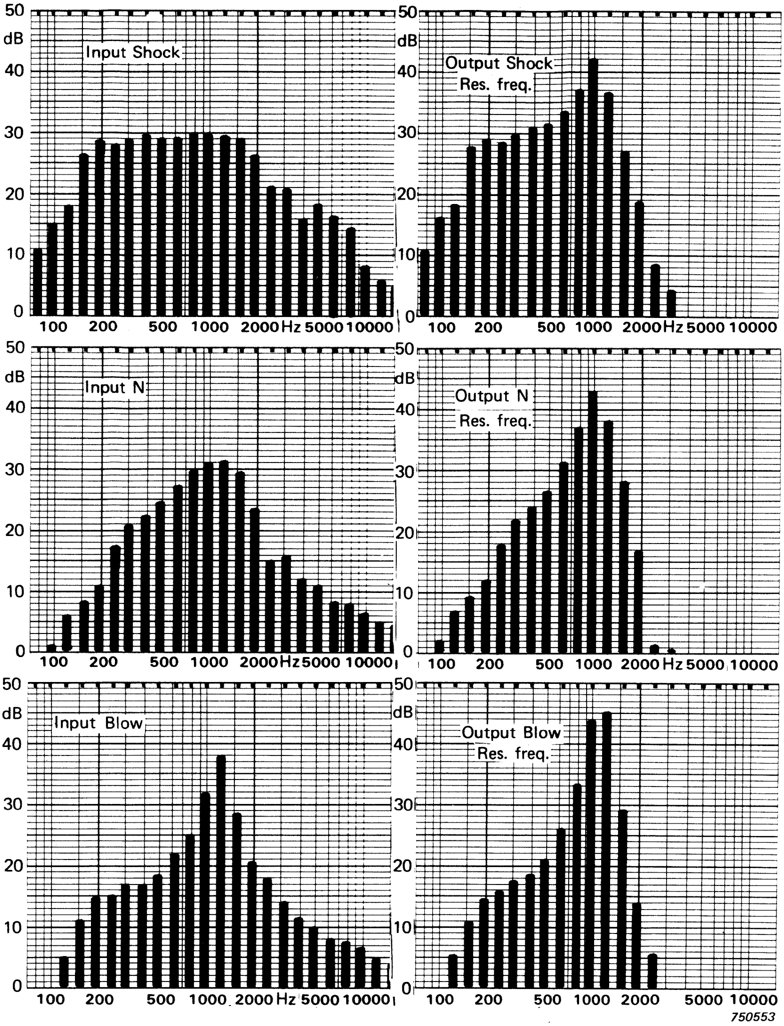


Fig.5A. Spectrograms of the input impulses shown in Fig.4A and of the corresponding output impulses at the resonant frequency of the filter

chanical movement of an object at supersonic speed, such as sonic bangs, projectile sounds, gunshots, explosions and even a whip-crack.

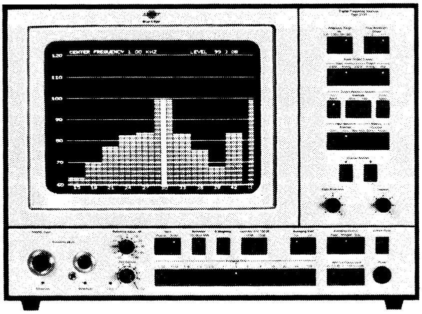
Near the source, the sound pressure curve has a sharp rise followed by a slower decaying rate of the pressure to just as large a negative value which then dies out abruptly. Such a pressure curve is often referred to as an N curve since the phenomenon resembles an N. After propagating for some time through the air, the higher frequencies are damped out to a greater extent than the lower frequencies whereby the N shape is modified to the form of a single period of a sine wave. Similar to the idealized shock impulse, the N shape impulse, when it is slow, goes through the filter without distortion. Around resonance, the first positive part of the wave is amplified by the same amount as for the idealized gunshot impulse, approximately 25%, whereas the amplification of the following negative part of the wave is considerably higher, approximately 2,16 times or 6,5 dB. In other words, a short impulse that is propagated through our outer ear can be 6 — 7 dB higher at the ear drum than the highest sound pressure outside the ear. During passage through the middle ear, a further similar amplification can occur, so that signals with a frequency content of 4 to 6 kHz would reach the inner ear with a total amplification up to 10 — 12 dB.

The negative part of the N curve being larger, explains also the apparent paradox that if an explosion outside a house is so intensive that the windows are shattered, the glass pieces always fall outside the house. The same occurs if a supersonic fighter flies rather low, the glass sides of a green-house when shattered, are as a rule slung out of the green-house. As in the case of the idealized shock impulse, the amplitude of the N curve also gets significantly smaller when the impulse becomes short.

Finally, the typical hammer blow which is characterised as a decaying sinusoid with many periods. Also in this case, the slow signal passes undistorted and without amplification through both the outer and middle ear. Around resonance, considerable amplification takes place and as seen from the spectrogram the higher frequencies of the signal are cut-off. For still shorter impulses, the amplitude is damped just as in the case of the previous impulse forms.

News from the Factory

Digital Frequency Analyzer Type 2131



As the name suggests this real time analyzer is almost entirely digital in operation as it uses digital techniques for filtering, RMS detection and averaging. It is designed to measure and display on a large calibrated screen either 42 1/3 octave channels having centre frequencies from 1,6 Hz to 20 kHz or 14 1/1 octave channels having centre frequencies from 2 Hz to 16 kHz together with a linear channel. The input signal may be A weighted prior to analysis, if required, in which case an A weighted spectrum is then displayed and the linear channel (in octave mode) gives the A weighted input signal level.

The digital techniques utilized by the analyzer not only have inherent advantages but also give the analyzer significant operational facilities. Among them is the extreme ease of the use of the instrument on account of almost all the functions being pushbutton controlled from an electronic panel with LED indicators to show their status. They can also be remotely sensed and controlled from a B & K Computer Type 7504 or from an IEC Interface Bus Controller if the optional IEC interface is fitted. The text for the data display which is calibrated in dB and channel number, is generated in Read only Memories. The calibration is automatically adjusted when the input attenuation or frequency range is altered. With the use of the channel selector, the centre frequency and amplitude of any of the channels can be read off the alphanumeric display on the screen.

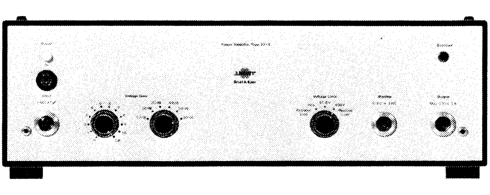
A digital memory is included for storing the spectrum which can be recalled to the display at a later time for comparison with newer data that can be held in an additional store. This store may also be used to hold the maximum level occurring in each channel, as well as be used independently of the memory for examination of analyzed data.

Facilities for output of the spectra from both the memory and the store are incorporated for analogue and digital peripherals. The built-in interface for digital output permits direct connection to a Computer Type 7504 or a Tape Punch Type 6301 in which case the punched spectra may be re-entered into the 2131 store (via a Tape Reader Type 7102) for long term storage of reference spectra.

Apart from the facts that the digital filter has better controlled filter shape, greater freedom from drift and requires no special trimming to maintain its properties as components age, the most significant advantage is that it greatly simplifies the use of a digital detector and a digital averager. The digital detector permits true RMS detection without crest factor limitations, while the digital averager permits both linear and exponential averaging. In both modes 13 different averaging times from 1/32 s to 128 s in a binary sequence can be selected. To obtain the same statistical accuracy in each channel for measurements on random signals, exponential averaging can be used with a fixed 68% confidence level for $\sigma < 1$ dB, $\sigma < 2$ dB or $\sigma < 5$ dB.

Finally a reference voltage of 100 dB RMS referred to 1 μV is built-in for calibration and can be adjusted in steps of 10 dB through a range of ± 50 dB.

Power Amplifier Type 2713



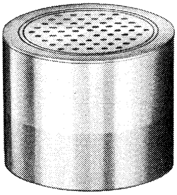
When a high capacitive transducer such as a Standard Hydrophone is used as a transmitter, the driving voltage should be high to obtain the best possible signal to noise ratio at low frequencies where the transmitting sensitivity is low. This is turn leads to a heavy current at high frequencies where the transmitting sensitivity is higher. Also the driving amplifier must deliver a constant voltage without being influenced by the capacitive loading presented by the hydrophone and cable.

These special requirements, which place severe demands on the output section of the Power Amplifier, are fulfilled by the Type 2713 which can deliver 100 VA into capacitive loads up to 30 nF while maintaining a good signal to noise ratio.

The Power Amplifier has a frequency range 10 Hz to 200 kHz with a maximum gain of 60 dB in 10 dB steps with continuously variable gain in each step. In order to protect the transducer, switchable voltage limits of 100 V RMS for reactive loads, 75 V RMS for resistive loads or 31,6 V RMS for both reactive and resistive loads can be selected.

Precautions have been taken to prevent damage to the amplifier and the transducer due to overload or overheating. Also an overload lamp as well as a socket for monitoring the output voltage are incorporated.

Condenser Microphone Cartridge Type 4160



The 1″ Condenser Microphone Cartridge Type 4160 is an equivalent to the condenser microphone WE 640 A manufactured by Western Electric. As Western Electric has ceased the production of WE 640 A, B & K has, in agreement, started the production of Type 4160 as a successor of the WE 640 A.

Type 4160 is a backvented 1″ pressure microphone mainly intended for coupler measurements (e. g. reciprocity calibration) and as a laboratory standard. It fulfils the ANSI S1.12-1967 standard for laboratory standard microphones types L and XL.

This microphone is very similar to Type 4144 but is equipped with a gold plated adaptor at its front (similar to Adaptor DB 0111) to provide the front volume required by the standard. The adaptor is permanently fixed to the microphone to ensure minimum leakage from the front volume cavity when the microphone is used in couplers filled with hydrogen. A gold plated protection grid (similar to DD 0015) is also included. The microphone is delivered with a normal calibration chart, except for the frequency response which is recorded as an actuator characteristic in a helium atmosphere giving a response curve which is similar to the real pressure response.