On the Sensation and Measurement of Loudness

by Ulrich Steudel

Communication from the Institute for Low Current Technology, Dresden Technical University

This English translation of Ulrich Steudel's 1933 paper *Über Empfindung und Messung der Lautstärke*, Hochfrequenztechnik und Elektro-Akustik 41, [1933] booklet 4. S.116, was kindly provided in February 2016 by Harvey A. Smith, Professor Emeritus of Mathematics at Arizona State University.

Word and PDF versions are available, together with a PDF of the original paper, at: http://realfield.com/anm/history/#Steudel-1933 as part of a project which aims to document the history of the measurement of low-level audio noise in a manner which produces a single figure (rather than, for instance, a multi-element spectral analysis) where that figure is a close match to the degree to which the noise disturbs a human listening to some other sound, such as music or speech.

This paper is the first in the timeline, and is a crucial document in the entire field. Thanks very much to Professor Smith for translating this long and detailed paper! Below is the translator's text, with changes only to formatting and a few typos.

Robin Whittle 12th February 2016

Contents

First the loudness of sundry noises, mostly clicks – single and periodic – were measured, in part directly by comparison with a 1000 Hz tone, in part by the indirect way through a differently calibrated comparison noise. Conclusions are then drawn from the totality of measurements, which have as their most important result the presentation of a new loudness formula that provides good approximations. The formula can also be extended to noises and tones.

In the second part, an objective phonometer and the analysis into components was used, which is capable of measuring an arbitrary sound, even a single click, without error.

I. On the Sensation of Loudness

A. Results of Measurement

1. Single clicks

The foundations of any noise are single clicks. It is therefore especially important to know their loudness, in order to draw conclusions about the loudness of a noise, which is their composition.

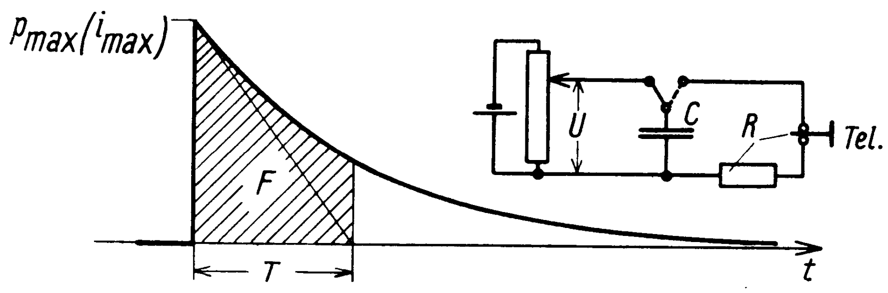

Fig.1 Pressure curve of a click (capacitor discharge) F = Area of the impulse formula (2) for T = CR = 0.3 msec.

Fig. 1 shows an easily produced click, for which the dependence of loudness on the maximal amplitude was at first investigated for larger time constants T (~1 msec.) This click was produced through the discharge of a capacitor via a dynamic telephone, that had a constant frequency response through all frequencies important to the ear, and with the constant [internal?] resistance had practically a real resistance. This telephone, which was the only one used for all measurements, was calibrated by Siemens & Halske and produced 2.4 mA_{max} = 1.7 $mA_{eff.}$ at 1000 Hz, pressed closely on the ear, an effective sound pressure of 1 bar at the ear apperture, equal to 70 Phon loudness[1]. Thus the pressure variation at the entrance to the ear canal can practically not be distinguished from the telephone current, at least below the chamber resonance (i.e. below 4000 Hz.)

The loudness of the click was measured with the Barkhausen sound meter [4]. The result is shown in Fig. 2. The ordinate displays the volume scale of a 1000 Hz tone defined in accordance with the determination by the A.E.F. as depending logarithmically on the pressure. The Barkhausen sound meter also has this scale. Every measurement of loudness depends on *comparisons* of loudness. From Fig. 2 we learn that the loudness increases proportionately with the current, as does the loudness of reference tone of 1000 Hz (45° line), except for the range of small loudness under 40 Phon L. That means that, in the click, not just extreme frequencies are important for the loudness, but mainly the most audible in the range between 30 and 3000 Hz, for here the ear sensitivity curves [2, 11] in the range of higher loudness are still almost parallel. Fig. 2 shows the measured values for nine persons with normal ears.

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[1] "Phon loudness" or, shortly, "Phon L" means the "loudness"defined by the A.E.F. 20 Phon equals a ratio of 10:1 in pressure, while earlier one took 1 Phon to equal a pressure ratio of 2:1.

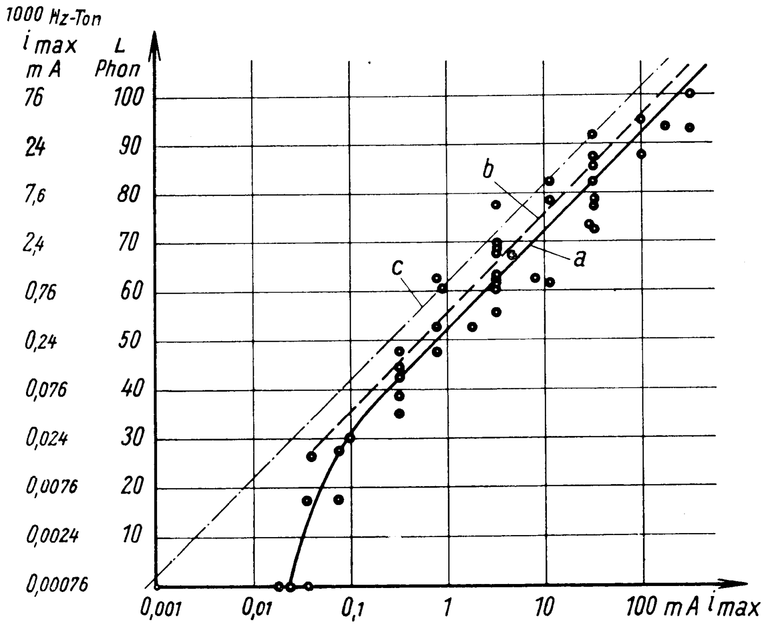


Fig. 2 Loudness of a single click like Fig.1 with T = 1msec.

a – Trend of the measured values for 9 persons.

b – Graph of the new objective apparatus, i_{max} = current peak in the dynamic telephone.

c – Loudness of a 1000 Hz tone of the same i_{max}.

The individual values are strongly scattered. It is caused by the individual sensitivity variation, which can change in a short time of its own accord or from a trial measurement. Sensitive persons measure more the degree of annoyance, and not the loudness. The difficulty is clearly this, that for the actual measurement only the unusually short time of the click is available. Doubtless, however, such a measurement could be much practiced. Four persons who had practiced longer at measuring clicks arrived without mutual influence at much less scattered results, both individually and between one another. From these, the loudness of a click can be determined with great accuracy. It is important that one allow such persons to conduct the measurements who are suitable to learning it. It was often observed that a person formed a reproducible but false concept of loudness, and with this measured sure but false curves. The falseness resulted from the fact that a click *a* with a greater maximal current compared to a 1000 Hz tone is measured as softer than a click *c* with a smaller i_{max} although upon direct comparison between *a* and *c* the difference is given correctly. That is, these people, upon direct comparison, have judged a sound *b* louder than *a* and *c* louder than *b*, upon direct comparison, however they judged *a* louder than *c*. It is especially advisable in taking measurements of this sort of test to make repeated comparisons between *a* and *c*, for only then is the proper method of collecting the data guaranteed. One can also proceed so that one can adjust *a* = *b* and *c* = *d* and then, as a test, compare the four differences between *a-c* and *b-d* as well as between *a-d* and *b-c*. In this, for instances, *b* and *d* can be 1000 Hz tones of various loudness and *a* and various loud clicks. *It is therefore not always right to use inexperienced people if possible for measurements of loudness.* This viewpoint was considered in the drawing of the average curve in Fig. 2, which will serve as the calibration curve for the subsequent measurements.

Fig. 3 shows the decrease of the loudness of the same click with the maximal amplitude held constant, but *T* reduced, i.e. the current that immediately rose to i_{max} is allowed to decay more or less slowly. The measurement here is very precise, if the calibration curve of Fig. 2 is applied to the comparison of loudness of a click. It is thus a click with constant i_{max} (Telephone current, which is on every curve) and various *T* (Abscissa) with a click of constant *T* (1msec.) and various maximum currents (ordinate, with the application of the calibration curve *a* in Fig. 2) adjusted to the same loudness.

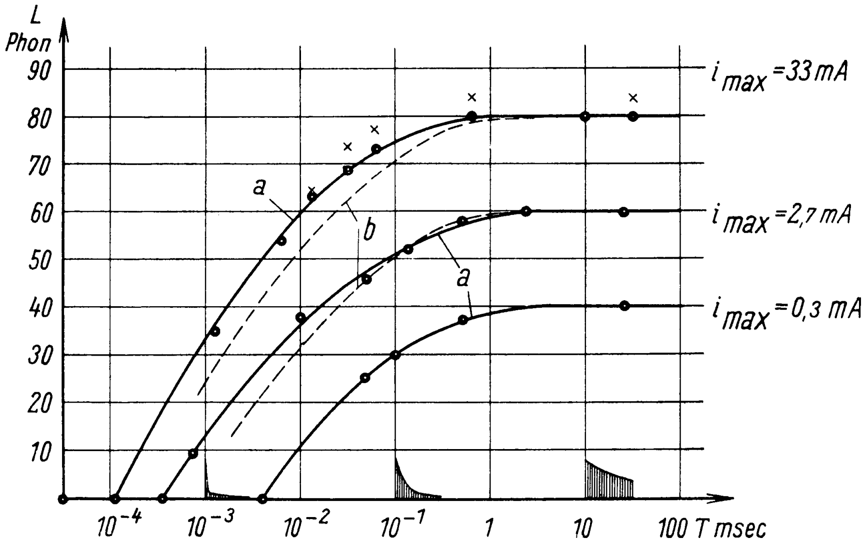


Fig. 3 *a* Loudness *L* of a click like Fig. 1 depending on the time constant *T*. (Measured by comparison with clicks like Fig. 1 with T = 1msec. and various i_{max}. Based on curve *a* of Fig. 2 for $L = f(i_{max})$.)
b Computed according to formula 2. X display of the objective apparatus for i_{max} = 33mA.

In order to understand the elementary components of a noise, it is also important to investigate the loudness intensity of clicks with other forms of pressure curves. For this purpose the following investigation was carried out:

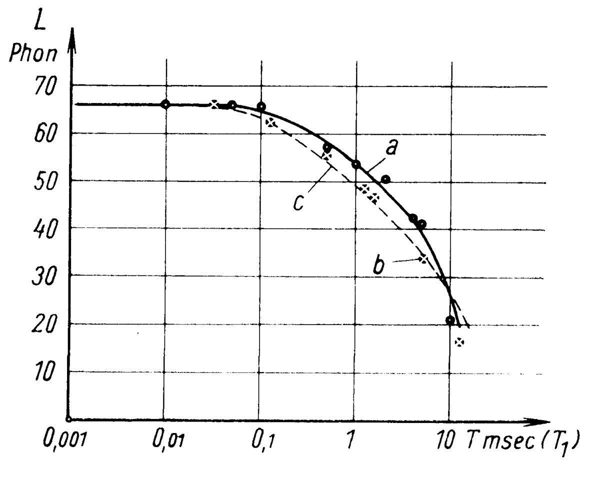


Fig. 4 Influence of the increase time constant on the loudness. *a* Circuit of Fig. 5, I_{max} = 5ma. *b* Rise in the form of Fig.6, I_{max} = 5ma., $T = 2.6(LC)^{1/2}$ *c* calculated according to formula (2).

Fig. 4 shows the dependence of the loudness of an increase of pressure on the speed of the increase. The dynamic telephone, used as voltage measuring device with a large series connected resistance R_1, was switched parallel to a capacitor C, which could be charged through a specified current source resistance R_2, to the voltage U. The current flow in the telephone shown in Fig. 5 resulted.

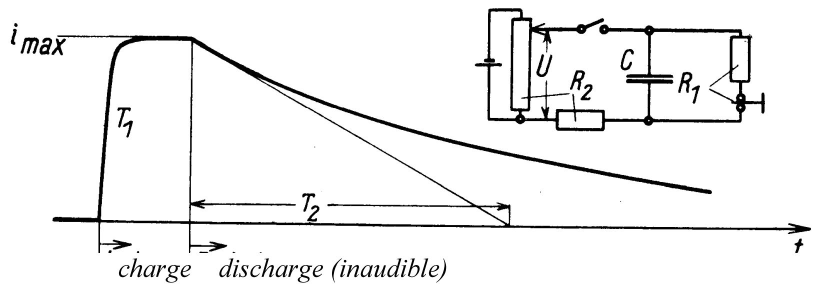


Fig. 5 Pressure curve of a click (Telephone current).

Since $R_1 \geq 50R_2$, $T_1 = CR_2$, $T_2 = CR_1$, and $i_{\max} = U/R_1$, approximately. T_2 is so chosen that the decreasing pressure is inaudible. T_1 could be changed through R_2 and C. The value of $i_{\max}$ was constantly 5 mA. The loudness of click resulting from the charging of C was measured in comparison to a click of the type in Fig. 1. with T = 1 msec. the loudness scale of which is known (Fig. 2).

The dependence on T_1 yields the curve *a* in Fig. 4. The limiting case $T_1 = 0$ (really, $T_1 < 10^{-4}$ sec.) is identical with the limiting case T = infinity (really T > 10^{-3} sec.). All these comparison measurements of clicks, even though they have very diverse sound characters are truly exact; departures of more than ±2 Phon in individual measurements are few.

In order to understand also the loudness of clicks that don't *begin* immediately with the steepest pressure increase, the capacitor in the same circuit was charged through an inductance L the magnitude of which resulted in exactly the non-oscillatory limit ($CR^2 = 4L$). The current in the telephone is then:

$$i = i_{\max} \cdot \left(1 - \left(1 + \frac{t}{\sqrt{LC}}\right) e^{-\frac{t}{\sqrt{LC}}}\right) \qquad i_{\max} = \frac{U}{R_2 + R_L},$$

where R_L is the coil resistance. The curves in Fig. 6 show the development of this current.

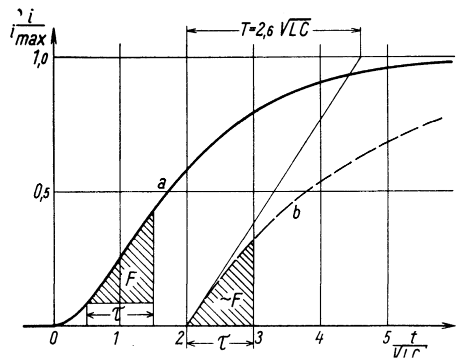


Fig. 6 *a* Current increase in the non-oscillatory limit.

b Exponential function with the same slope (T = 2. 6$(LC)^{1/2}$).

F = *d*etermining area for formula 2 when $(LC)^{1/2} = \tau = 0.3$ msec.

Finally, the sound amplitudes were investigated of clicks that occur when the discharge current of a capacitor flows through the telephone over an inductance. Again, in each case, the non-oscillatory limiting case was set. The current then followed the rule:

$$i = \frac{U}{R}\frac{2t}{\sqrt{LC}}e^{-\frac{t}{\sqrt{LC}}}\ ;\ \sqrt{LC} = \frac{C \cdot R}{2}$$

if the capacitor was previously charged to the voltage U. The curves in Fig. 8 show the development of this current. Again, U/R = 10 mA was kept constant and $(LC)^{1/2}$ varied. (This time, $i_{max} = 0.74U/R$!). Curve *a* in Fig. 7 shows the dependence of the loudness on $(LC)^{1/2}$.

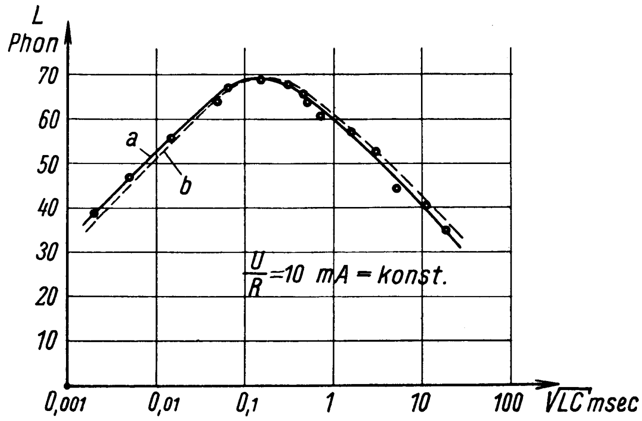


Fig. 7 *a* Loudness of a non-oscillatory click (Fig. 8). *b* Calculated according to formula 2.

For all measurements of the comparison of two clicks, a multipolar switch with two positions was used, which was controlled by the measuring person. One position provided the comparison click and the other that to be compared. The click which didn't use the telephone was prepared in each place (e.g. the capacitor charged). The measurement turns out so very simple and sure that one blamed the click itself [?] and can concentrate on the moment of measurement. Apart from the measurements in Fig. 2, I have carried out alone the comparison measurements of clicks, but also taken many samples from other persons. In any case, they never exceed the error bounds of ±2 Phon.

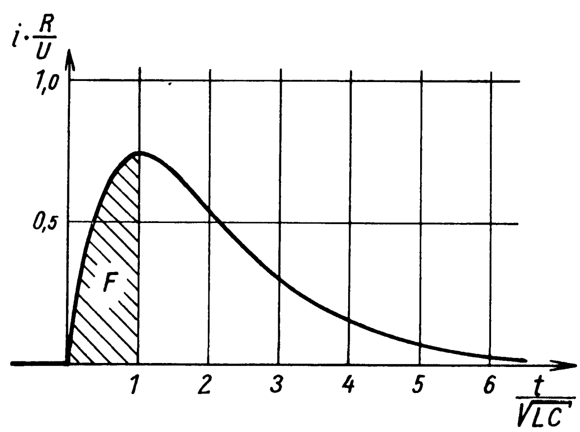


Fig. 8 Charging of a capacitor in the non-oscillatory limit. F = Area for formula (2) with $(LC)^{1/2} = \tau = 0.3$ msec.

2. Repeated Clicks, Noises

As the gradual transition from clicks to the measurement of the loudness of noise or tones, we have the following two objectives:

The loudness of clicks in the form of a damped vibration should agree, upon comparison, with the known click measurements. They should be produced through amplification of an oscillation with a tube in the dynamic telephone. A change-over switch gave, in one position the non-oscillatory and, in the other, the oscillating click (frequency 1000 Hz). The loudness of both was then measured with the Barkhausen sound meter. Eight persons have measured in the loudness range from 50 to 100 Phon. Immediately the correctness of the logarithmic noise intensity scale in this range (Fig. 2) was again confirmed. Further, Fig. 9 gives the dependence of the loudness of the oscillating click with this time constant for fixed i_{max} (given on the right by each curve). This is once again a good confirmation of the measurement of the loudness of a single click in Fig. 2, for a continuous transition from a 1000 Hz tone (T = infinity) to a single click ($T < 0.003$ sec), because the tonal characteristic starts at around intensity of 85 Phon just when $T = 3$ msec. and at 45 Phon when $T = 6$ msec. Nevertheless, the experimental values spread on the average ±8 Phon. Fig. 9 shows the average values.

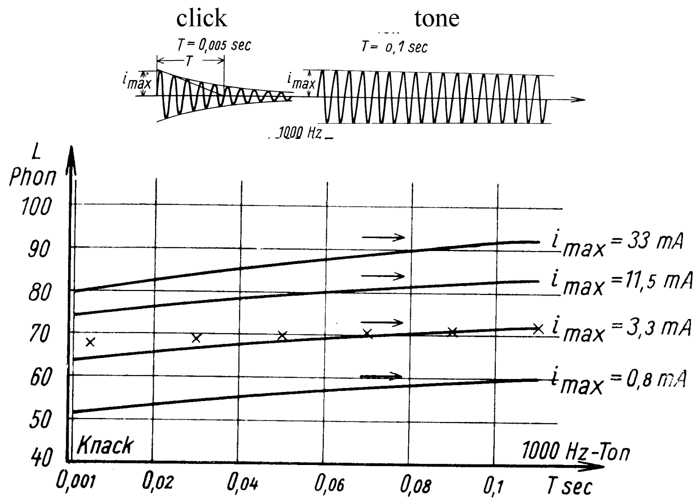


Fig. 9 Loudness of a fading 1000 Hz tone. x display of the objective apparatus for I_{max} = 3.3 mA. Arrows indicate loudness of a sustained 1000 Hz tone of the same amplitude.

The plot of the curves is exact to ±4 Phon, but not their absolute height (compare the dispersed values in Fig. 2). For $T = 5$ msec. where perhaps 50 complete cycles are audible, the oscillating click has about the same loudness as a non-oscillating click ($T > 1$ msec.) of the same maximal amplitude, and is about 10 Phon softer than a similar 1000 Hz tone of the same amplitude.

Fig. 10 shows the frequency dependence of the loudness of the clicks of Fig. 1 with $T = 0.6$ msec. The measurements were again made with the Barkhausen sound meter. It gives the average of the measurements by three experienced persons. The range of variation is smaller for higher frequencies (±4 Phon) than for lower frequencies (single click, ±8 Phon). The loudness grows about 10 Phon with increasing frequency and then reaches the loudness of the 1000 Hz tone of the same amplitude. At still higher frequencies (over 80 Hz) it practically increases no more.

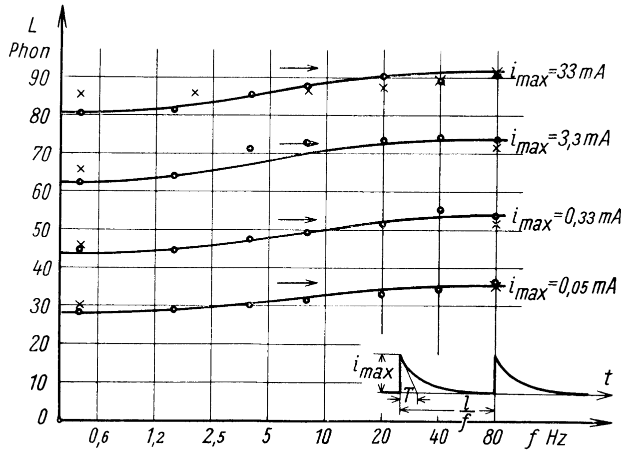


Fig. 10 Loudness of oscillatory clicks. o–average values. Display of the objective apparatus Arrows indicate loudness of a sustained 1000 Hz tone of the same i_{max}.

Finally the dependence of loudness on the phases of sinusoidal components for strong peak-containing noises was investigated. Buzz, in Fig. 23*a* records a 12 member phase chain the time response curve of which is shown in Fig. 11. The amplitudes of the components were not changed in the phase chain. A lessening of the loudness of about 7 Phon compared to the direct tone given by the telephone resulted from the phase shift. Indeed, Helmholtz had predicted a dependence on the phases for such noises.

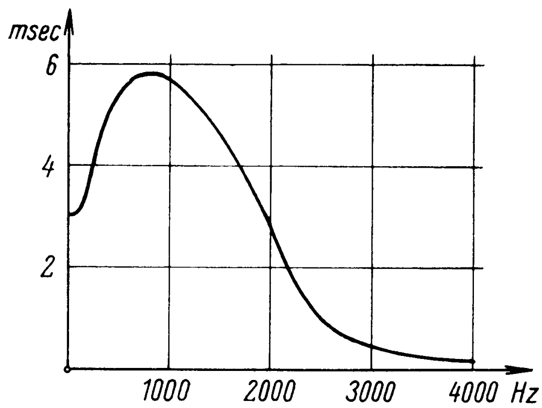


Fig. 11 Time response curve of the Siemens phase chain (12 resonant members).

3.Decay of Loudness

In order to be able to say something about the decrease of the loudness after the cessation of an excitation of the ear, the following experiment was done: one let a tone f_1 act on the ear for a long time (about 0.5 sec.) on the dynamic telephone and interrupted it briefly, preferably periodically. One introduces on the telephone at the same time, a continuous slightly higher tone, f_2, the current of which is slowly increased from a small value. It will at first be covered, until finally its presence becomes noticeable through change in the sound characteristic of the interrupted tone f_1. The current of the covered tone f_2, when it is just noticeable, is then a measure of the smallest occurring loudness in the covering tone f_1. One thus obtains the loudness for which the original loudness of f_1 is buried during the period of interruption. For a true loudness yardstick, it is just necessary to consult the known covering curves of the two tones (Fig. 13).

Figure 12 shows the result: It is the smallest loudness determined from Fig. 13 of the interrupted f_1 vs. the interruption time. Thus it shows the loudness, shortly after it is shut off, of tone f_1, which is shut off at time $t = 0$. An inexperienced person measured curve *a*. The click, during the moment it is shut off, apparently induces with its other character an increase in loudness. Thus, if the clicks followed one another with sufficiently small separation, the covered tone must be made louder in order to produce a noticeable change in the tone image in contrast to its absence; thus the number of cycles in the break must be increased. Clearly, however, this loudness increase is not real, at least not in reference to its power to cover, for upon very attentive observation one clearly notices the covered tone. One could compare this apparent loudness increase with the Mach bands[2] in vision, which depend on contrast. Here the characteristic of the change from tone to noise (click) is in the ear. That sort of "acoustic cheating" makes the measurement very difficult.

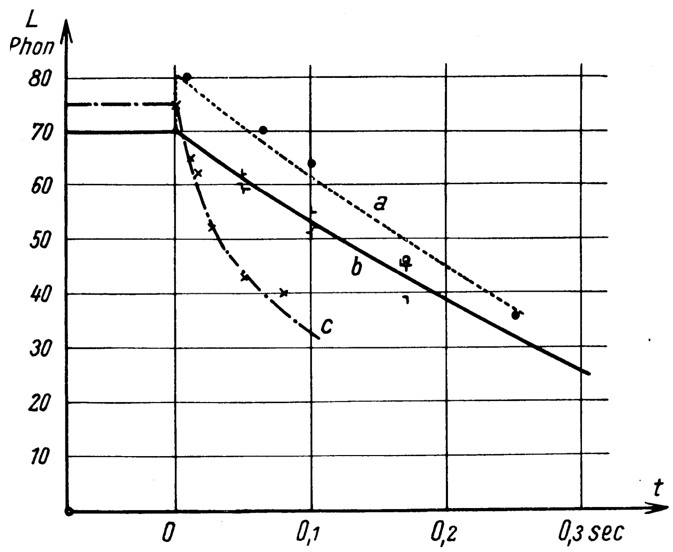
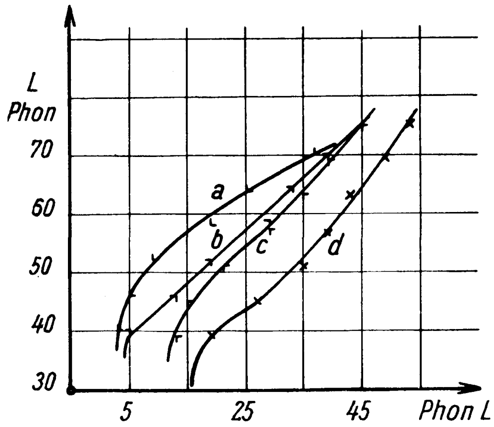


Fig. 12 Perception of the loudness of a tone after switching off.
a Inexperienced measurer.
b 480, 850, and 1850 Hz tones.
c Periodic clicks.

[2] Translator's note – Mach bands are an optical illusion in which the contrast between edges of slightly different shades of gray as soon as they contact one another by triggering edge detection.

Curve *b* shows the Loudness perception of a concentrating measurer. It is, as the experimental values show, independent of the pitch in the range from 400 to 2000 Hz. It is improbable that the development time [3] of the covered tone plays a decisive role in this method of measuring the loudness decrease, because it is really is continuously there and one increases it just until one hears a change in the broken tone, not until one hears the pitch of the covered tone.



Loudness of the covered tone f_2

Fig. 13 Covering curves for Fig. 12 The ordinate is the loudness of the covering tone f_1

a f_1 = 1784 Hz; f_2 = 1784 Hz.
b f_1 = 800 Hz; f_2 = 850 Hz.
c f_1 = 431 Hz; f_2 = 480 Hz.
d Periodic clicks @ 80/sec. in accordance with Fig.1 ($T = 10^{-3}$sec.); buzz Fig 23*a.*

If a repeated click of Fig. 1 with $T = 10^{-3}$ sec. is chosen in place of the tone f_1, the curve *c* in Fig. 12 results. The abscissa here displays the interval between two successive clicks. A buzz (Fig. 23*a*) is substituted for f_2. Naturally the coverage curve, Fig. 12 must be taken with continuing full volume of the click; this is practically achieved at about 80 Hz. In all the curves of Fig. 12 the softer values below 40 Phon can no longer be recorded because of the unfavorable shape of the coverage curve in Fig. 13.

B. Consequences for the Evaluation of Loudness

1. Single Clicks

From the totality of the preceding investigative results, one can draw the following conclusions:

The human ear only reacts to changes in air pressure. (1)

These changes must be sufficiently rapid in order to determine a feeling of loudness (a 10 Hz tone is inaudible) and must not be cancelled after a very short time by an equally large opposing change, otherwise, despite strong pressure changes, a feeling of loudness can scarcely be detected (e.g. 10,000 Hz tone.)

From Figs. 3 and 4 it can be seen that for the loudness of the click only an initial short portion of the pressure curve is important because the entire time is inconsequential for the loudness. From Figs. 3 and 4, the critical time is about $3\text{x}10^{-4}$ sec. Obviously, for the determination of loudness, one should consider *the area under the pressure curve* during this short time as an *impulse*. For that , however, only just the *most rapid* pressure increase or decrease is important, the area under this part of the pressure curve in the given time must be used (cf. Fig. 6.) Aside from that, the equal pressure portion is unimportant for loudness and must be discarded.

If L is the loudness in Phon *of a continuous 1000 Hz tone, p* is the effective sound pressure in bar, p_0 the effective pressure value in bar, then the loudness formula (according to the A.E.F.) reads by definition

$$L = 20 \cdot \log \frac{p}{p_0}$$

with

$$p_0 = 3{,}2 \cdot 10^{-4}\ \text{bar}_{\text{eff}} \qquad (70\ \text{Phon} = 1\text{bar}_{\text{eff}})$$

Upon consideration of the loudness measurements of *single clicks* a completely analogous formula can be set up:

$$L = 20 \cdot \log\left(\frac{1}{P_0} \cdot \frac{1}{\tau} \left[\int_{t_0}^{t_0+\tau} (p - p_0)\, dt\right]_{\max}\right). \tag{2}$$

Valid for $L > 50$ Phon

Here again L is the loudness of the click in Phon, $p = p(t)$ the instantaneous sound pressure in bar (at the entrance to the auditory canal), p_0 the pressure at the time t_0 in bar, τ the short important time, which we will call the **impulse time**, $\tau = 3\text{x}10^{-4}$ sec. and p_0 a constant threshold value in bar. The time t_0 must be chosen so that the integral is maximized. It is therefore all the same, whether $p(t_0)$ is larger or smaller than $p(t_0+\tau)$. The threshold constant value, P_0 can be calculated, for instance, from a value in Fig. 3 and the known telephone efficiency. We choose, for instance, a step current rise, so T = infinity and read off from Fig.3 the average value: For $i_{\max} = 3.3$ mA, $L = 62$ Phon. The maximal value of the integral in equation (2) will be $3\text{x}10^{-4}$ x 3.3 mA. Since the efficiency of the dynamic telephone is 1bar = 1.7 mA, if it is pressed on the ear, this is ($3\text{x}10^{-4}$ x 3.3/1.7) bar-sec. It is nearly independent of frequency. Naturally the sound pressure must always be taken at the entrance of the ear canal. Equation (2) now yields

$$10^{\frac{62}{20}} = 1260 = \frac{1}{P_0} \cdot \frac{1}{3 \cdot 10^{-4}} \cdot \frac{3 \cdot 10^{-4} \cdot 3{,}3}{1{,}7},$$

$$P_0 = 1{,}5 \cdot 10^{-3} \text{ bar}.$$

This threshold value P_0 is equal to the value at which curve *a* cuts the abscissa in Fig.2. multiplied by the efficiency of the telephone.

Equation (2) will be termed the *impulse formula* or the *area theorem*.

If one computes the values for Fig. 4 with the impulse formula, one obtains the curve *c*. The curve agrees well with the measured values. The points *b* in Fig. 4 must, at least for large *T*, correspond with the calculated *c*, for as abscissa the time constant of an exponential function with the same greatest slope (Fig. 6) applied and this greatest slope is appropriate for the loudness formula. They also correspond well practically everywhere.

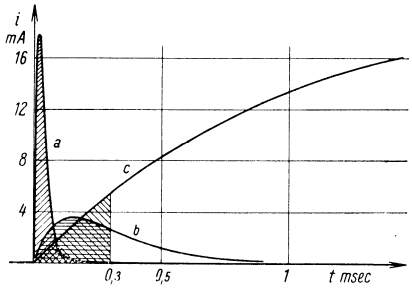


Fig. 14 Clicks of the same loudness of 65 Phon. i = current in the dynamic telephone.
a $(LC)^{1/2}$ = 0.018 msec. *b* $(LC)^{1/2}$ = 0.15 msec. *c*-$(LC)^{1/2}$ = 2.3 msec.

In Fig. 3 the calculated values *b* lie somewhat lower than the measured values; but the path is very well reproduced. In Fig. 7 the values computed according to the formula are similarly entered as curve *b*. The agreement here is perfect. One must consider that the agreement is not only relative, but absolute! To better illustrate, in Fig. 14 three different pressure curves with values from Fig. 7 have the same loudness (65 Phon) recorded full scale with the areas relevant to the loudness. It is astonishing that such different looking pressure curves (and they would have been able, had the page permitted, to have been portrayed much more extremely) have precisely the same loudness, of which many persons have convinced themselves. To provide a good understanding of the impulse formula (2), in all figures that reproduce pressure curves, the areas specified by the formula are cross-hatched.

2. Repeated Clicks, Noises

From Figs. 9 and 10 one must observe:

> *If the repetition of the pressure impulse causing periodically repeated clicks occur more than 50 times per second, the loudness of the periodically repeated clicks is increased by about 10 Phon compared to a single click.* (3)

If the time between clicks is greater than about 50 sec. then the loudness does not increase further. Thus one can view a noise with a click-frequency of more than 50 Hz as a persistent excitation of the ear. For instance, a 1000 Hz tone is a persistent excitation. Fig. 9 shows how the loudness depends on the *duration of the excitation*. At *one* click per second we are still dealing with single clicks, i.e. after every excitation of the ear, such a long time passes that the ear again returns to the initial rest condition. It should be expressly noted that these remarks only hold approximately for a loudness range from 50 to 100 Phon. For lower sound intensities the conditions change.

Upon consideration of Proposition (3) the loudness formula (2) (the impulse formula) can be applied for arbitrary noises and tones, so long as they are not under 50 Phon in intensity. One must only consider the following: If such an area, as expressed in the formula, appears more often than once per second in the pressure curve of a sound, then, according to Proposition (3), then an increment of about 10 Phon must be made to the value of L obtained from the formula, the magnitude of this results from the dependence on this frequency by Fig. 10.

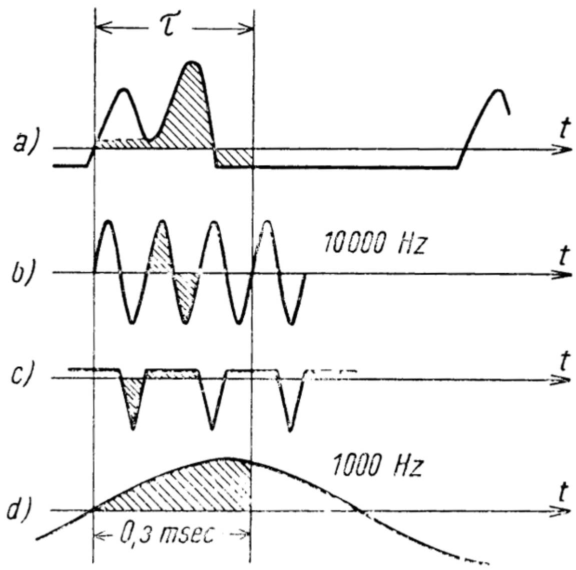


Fig. 15 The areas F of the loudness formula (2).

The following criteria seem to me to be the best for the correct choice of area in each case: Fundamentally, the area must be enclosed by the pressure curve and the null-line (i.e. the null-line that is produced if one draws the pressure curve as a simple change pattern.) Then the area is determined unambiguously, other than with single clicks the pressure curve from a pressure p_1 produces a residual pressure p_2. Then one could as well take p_1 as p_2 for the null-line. However, if one chooses the null-line, in this situation, so that the impulse area is a maximum, then the error can scarcely exceed a factor of 2 (6 Phon). The impulse area must be split in two, because the area *under* the null-line must also count as positive. The ear cannot distinguish between an increase and a decrease in pressure. The maximal area is always what is significant for the loudness: it can therefore arise even in the case of falling parts of the pressure curve. If the pressure curve of a sound appears to be such that not just *one* pressure increase and decrease occur within 0.3 msec. in the area to be sketched, then one may simply compute the area from the same pressure values which pass through in the same sense. The integration of formula (2) may thus be extended over two equal pressure values if the one occurs in the increasing and the other in the decreasing portion of the pressure curve. Integration may not be extended over more than two equal values [curves?]. Fig. 15 shows, as an example, several pressure curves and the maximal areas found according to the above methods. Because all curves are of higher periodicity, according to Proposition (3) another 10 Phon must be added to the result from the impulse formula.

If one investigates by this method the dependence on frequency f of the sound intensities of sinusoidal tones of the same amplitude then there results, below 1000 Hz, about a $1/f$ curve, from 1000 to 3000 Hz. the loudness remains approximately constant, and above 3000 Hz approximately an f curve. This curve provides a rough, but still reasonable approximation to the ear sensitivity curve for 70 Phon (References [2,11].) Fig. 16 shows both curves.

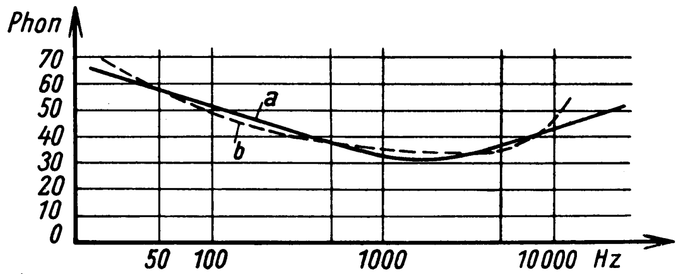


Fig. 16 Adjustment of the a-computed value, according to formula (2) for sinusoidal tones.
a-according to the ear sensitivity curve, *b*- for L = 70 Phon, according to Fletcher.

If one computes the loudness of a 1000 Hz tone of 1.4 bar amplitude according to the impulse formula (2), for instance, the result is 57 while an addition of 10 Phon equals 67 Phon compared to the known value of 70 Phon. It must be considered, however, that the impulse formula alone, derived from the clicks of Figs. 3 and 4 and the impulse time, and the threshold constant P_0 is calculated. The transition to a periodic sound occurs only through Proposition (3), derived from Fig. 10. Therefore the above agreement for a 1000 Hz tone can be well-defined, particularly, one knows from Fig. 16, that the agreement for other sinusoidal tones (e.g. 500 Hz) is still better.

Naturally the impulse formula (2) cannot be called an approximate formula because it is found purely empirically. Nevertheless, its physical form is not very strange, for it clearly appears that the *impulse* is primarily responsible for response of the ear to the loudness. In any case, from the impulse formula and the fact of the slow decay of the loudness (Proposition 4) as well as the existence of Proposition (3) it comes out that the nerves of the ear do not react linearly with regard to the perception of loudness. Thus the loudness is not simply determined by the decomposition of the pressure curve itself into independent sinusoids obtained from a Fourier series or integral (see below.) A consequence of that is the known dependence of the loudness on the phase of the components. For that reason, attempts to determine the loudness of a click by weighting the components of the Fourier decomposition by using an ear sensitivity curve or various other overlays must fail. For this reason, the *curve form* is more important than the sound spectrum in evaluating loudness.

The dependence of the loudness of an 800 Hz tone on the speed of onset investigated by von Békésy ([3] p. 118, Fig 6) can be very prettily explained. In these curves impulse formula (2) is important for very short times (~0.01 sec.); the loudness climbs momentarily to a value of about 10 Phon smaller than the final value for continuous activation. For longer times (up to 0.2 sec.) Proposition (3) must come into play, so according to Fig. 9 the loudness still gradually increases by about 10 Phon.

3. Decay of Loudness

In contrast to the very short time of 0.3 msec., which is important for the magnitude of a developing loudness, the vanishing of the loudness upon ending the disturbance occurs much more slowly (cf. Fig. 12).

The loudness decays in a time of the order of magnitude of 0.5 sec.[3] (4)

The previous disturbance was, according to curve *b* of Fig. 12, one lasting ~0.5 sec. If the stimulation of the ear lasts but a very short time, as in a click for instance, then the decrease of loudness goes a bit faster as curve *c* shows.

The decay of the loudness is dependent on the duration of the previous disturbance. (5)

The Propositions derived here can provide resolution to many inexplicable seeming loudness reactions to noise.

4. The Physiological Processes of the Reaction to Loudness

How can one now portray the process of loudness perception by the ear? The foundations of the Fletcher theory [16] will be accepted as presupposed. Upon the reception of clicks the basilar membrane appears as a uniform membrane (as in a telephone) with very small mass and large damping. The mass must be small because of the small time τ in formula (2) and the damping large, otherwise the settling time would be large and vibrations would appear during settling. Just as a telephone membrane can exhibit various modes of vibration upon excitation by different sinusoids, it also appears that the basilar membrane can exhibit various responses. The sharp formation of these vibration modes, however, does not just occur at specific frequencies, but a particular form of vibration having not merely stationary nodal lines, but also the superposition of standing and propagating waves occurs for every audible sinusoidal tone[4] {cf. Fletcher 16). If one considers only the standing waves then each audible sinusoidal frequency corresponds to a particular resonance of the basilar membrane.

---

[3] That the decrease of loudness is independent of the frequency stands, up to a certain point, in contradiction to the fact that one can hear more rapid variations [?] with high notes than with low. On the contrary, very high tones appear to resound very long.
[4] [Translator's note: I believe this and the following remarks are true for *any* membrane, including telephone diaphragms.]

One could thus also compare the membrane with a series of coupled resonators (a vibrating-reed frequency meter), but the damping of the resonators is very large. Upon the sensing of a tone, which is strongly distinguished from sensing a noise, the nerve fibers distributed along the basilar membrane sense the "image" of the vibrating membrane; naturally, only if it is in the steady state. In this manner it is possible to distinguish slight differences in pitch despite the high damping of the individual resonances, because the collection of nerves is distributed so as to distinguish the small change in the vibration picture.

There is a continuous transition between tones and noises that doesn't, however, depend only on greater or less periodicity. For instance, a periodic sound must be called a noise if it has sharp peaks that deflect the entire ear membrane and obliterate each vibration. I would like to propose, as a measure of the noise-character, the relation of the peak values to the effective values, aside from the condition that no important periodicity lies in the range of good audibility.

As the investigations have shown, substantially the same criterion seems to hold for the sense of loudness both for clicks and tones (steady state vibrations.) Thus the particular waveform of the basilar membrane when excited by a tone cannot be of great significance. One can therefore rightly distinguish between the sense of loudness and the sense of pitch.
The validity of Proposition (3) is, in any case, based on the nervous system itself. The dependence the strength of excitation on the duration of the stimulus is known, within certain limits, for most sensory nerves [3, 22]. The same thing also holds for Propositions (4) and (5), which probably have their basis in the type of stimulus. There is a remarkable, analogy with the eye. Propositions (3) to (5) are also valid for the optic nerve. According to the above, the sense of loudness must be comparable to the sense of brightness, the sense of pitch to the perception of an image.

II. On the Measurement of Loudness

Independent of the theory of the perception of loudness by the ear, an appropriate objective measurement of a normal ear must be shown. Its result must be determined lie within the range of variation of many normal ears, preferably, if possible, near its average. If the range of variation is very wide, then the loudness is not clearly definable, and it is no longer appropriate to use an average curve.

One could now build an apparatus that displays directly the area defined by the impulse formula (2). However it would be extraordinarily complicated. I could imagine it, for instance, in the following way: The sound picked up by a microphone is divided between two circuits. In the first, the derivative is produced by an inductance and at its peak is momentarily switched, most probably electrically [= *electronically*?], which [closes on = *charges*?] a capacitor in the other circuit, but only for 0.3 msec. The capacitor becomes charged in this time by the speech [= sound?] stream; its peak voltage would be measured . After each discharge and peak voltage measurement it must be charged. Proposition (3) can indeed be satisfied by a suitable time constant of the voltmeter. The maximum in the impulse formula would be approximately achieved by the clearing [= discharge?] of the capacitor discharge during the derivative maximum. One can see that this sort of apparatus would pose monstrous technical difficulties.

Thus another way must be sought in which an improvement can be made in the principle of the previously-built objective sound measurer so that it yields appropriately to the expressed subjective feelings.

Fig. 17 shows the general scheme of an objective loudness measuring instrument. The filter-chain [Translator's note: Formally, the term *siebkette* used here means a series RLC circuit, but is often abused by using it for more general filter arrangements,] simulates a specific ear sensitivity curve, and its form may not be distorted in any part of the apparatus, otherwise even the sinusoidal tones will not be properly shown.

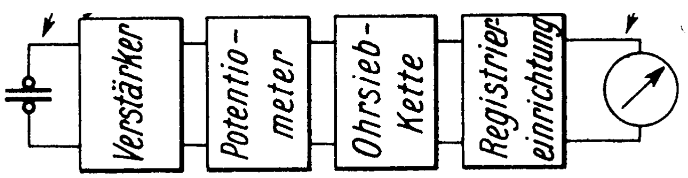


Fig. 17 Circuit, in principle, of an objective sound measuring instrument.
Verstärker = amplifier   Ohrsiebkette = ear simulating filter
Registrier einrichtung = recording mechanism

A fundamental recording apparatus was investigated:

1. Recording of effective values.
2. Recording of peak values.

In each case a calibration of the apparatus with a sinusoidal 1000 Hz tone corresponding to the A.E.F definition was made. The recording of the effective value gave results that were in part completely false, as is evident from the later figures. It has only proved suitable for the measurement of tone-like sounds and arbitrary noises in slightly damped rooms (Halls.) However the pure peak measurement (the impulse triode [32] was used exclusively) did not appear to be correct. One sees that best in Fig. 18.

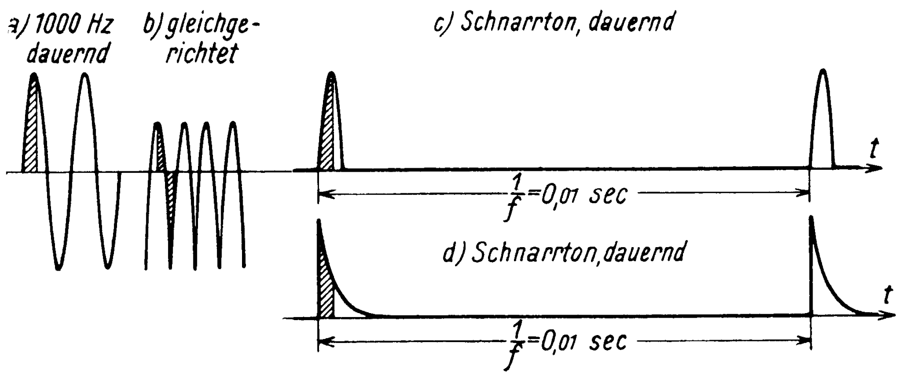


Fig. 18 To-scale pressure curves for approximately equal loud noises, valid for sound intensities from 50 to 100 Phon. The areas of formula (2) are hatched.

[Translator's note – *dauernd* means "continuosly." A *Schnarrton* is a buzz. Here *gleichgerichtet* means "rectified."]

All of the pressure fluctuations shown there are sensed by the ear as equally loud if they lie in the noise intensity range of 50 to 100 Phon. Heinze [23] has extensively investigated the loudness of tone *b)* in Fig. 18. He produced it by rectifying a 1000 Hz tone with a vacuum tube rectifier. I have investigated the loudness of *a)* and *d)* with many subjects; *c)* was created by a Schnarrsummer [Translator's note: some sort of buzzer] with a certain load; I produced *d)* as in Fig. 10, with a circuit-breaker controlled polarized relay that periodically charged a capacitor to a constant voltage through the dynamic telephone. The equality of the loudness of the pressure curves in Fig. 18 follows immediately from the impulse formula (2) (the areas are hatched there.) Here we learn the astonishing fact that

a 1000 Hz tone is about as loud as if only each twentieth half-wave of it is present

The peak values of the pressure curve in Fig. 18 would be the proper thing to display. However, the filter (for 70 Phon L) necessary in the loudness measuring apparatus reduces the peaks by about 5 to 110 Phon, while it simply passes the 1000 Hz tone through. Thus a simple peak measuring device behind the filter would not portray the pressure curve in Fig. 18 correctly. Additionally, one must introduce a two-way peak meter that will measure the *total* amplitude because of the frequently encountered unsymmetrical sound pressure curves.

Filter, R_1 = 1000Ω *amplifier* *1. rectifier* *2. rectifier*

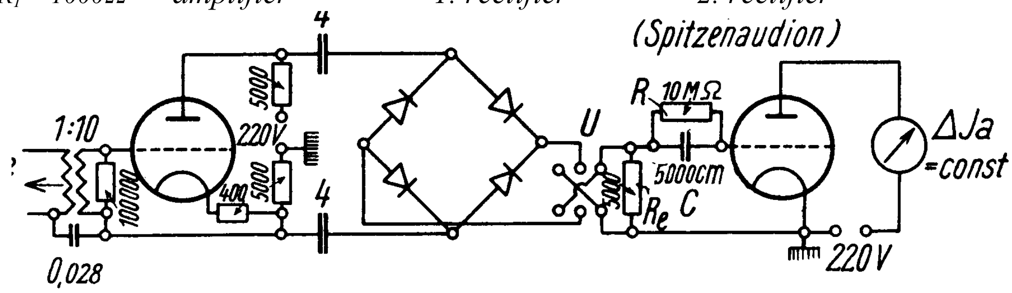


Fig. 19 Circuit diagram of the recording device of the sound meter with double rectification.

A maximum error of about 16 Phon could be introduced in this way. Nevertheless, in order to obtain a correct display for noises that contain strong peaks (for instance a motorcycle,) a second rectifier was introduced that caused the tone-like sounds to be displayed as a bit stronger in comparison to the noise-like sounds. Fig. 19 shows the complete circuit diagram in detail of this new tested recording apparatus.

For better understanding, we will first consider the two pressure curves *a)* and *c)* of Fig. 18 without a filter just as they are shown. Thus one can easily deduce with some consideration:

> *If the peak-triode (Spitzenaudion)* generally in ideal working order (broken characteristic, *C* very small, *CR* very large) in each voltage curve *the maximal value is reduced by the rectified value.*

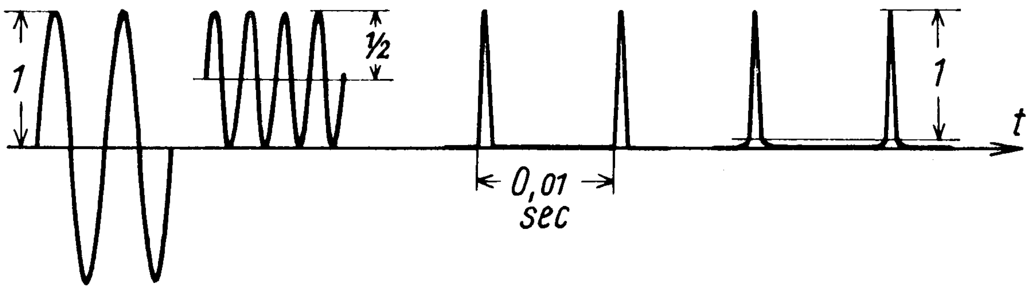


Fig. 20 The advantage of full-wave rectification.

Fig. 20 shows how, after a quadratic full-wave rectification[5] the 1000 Hz. tone has excursion 1/2 and for the noise of the same amplitude (Fig. 20 *b)*) however, the excursion remains 1. Upon simple half-wave rectification (peak measurement) the 1000 Hz. tone would be shown as 1, but, in fact, with the push-pull peak triode (which would be needed because of the frequently occurring unsymmetrical waveform of the sound) the value is 2. One realizes the advantage of full-wave rectification. One observes that by it what is lost through the filter is restored (the attenuation of all the peaks coming within 1/100 sec by about 6 Phon.)

In the second rectifier we can encounter only pure alternating currents, since the filter blocks direct currents. Indeed, the direct current component has no role in loudness. After the first rectifier, however, a direct current component is present in the current curve. If it is considerable, compared to the maximum current, it can cause a slight deflection [locking-out?] of the peak-triode. Indeed this does not show the maximum amplitude of the current curve, but reduces it by the direct current. In order to avoid this difficulty, [there is] a *polarity reversing device* designated *U* in Fig. 19 after the first rectifier. One could also replace it with a transformer circuit. One must calculate the excursion of the triode in each case.

---

[5] Translator's note: From Fig. 20 it appears that the signal is simply being squared, since $\sin^2 x = 1/2(1-\cos 2x)$ and the graphs of the clicks are shown as narrowed and their bottoms rounded, which they would be by squaring the signal.
I can find no reference for the meaning of the term *Spitzenaudion*, which I have translated as peak triode. (Audion was Lee de Forest's term for the triode, which he invented.) I conjecture from the figures that the term here means a triode operating in a region where the output approximates the square of a positive input – probably with a negative grid bias to cutoff. The full-wave rectification preceding the *Spitzenaudion* would be needed to keep the signal positive, and thus within the proper range to produce the squaring. A similar approach using vacuum tubes was used to create analog electronic multipliers by the quarter-square method

$$xy = 1/4\{(x+y)^2-(x-y)^2\}$$

in electronic analog computers marketed by George A. Philbrick during the early 1950s and used by the translator.

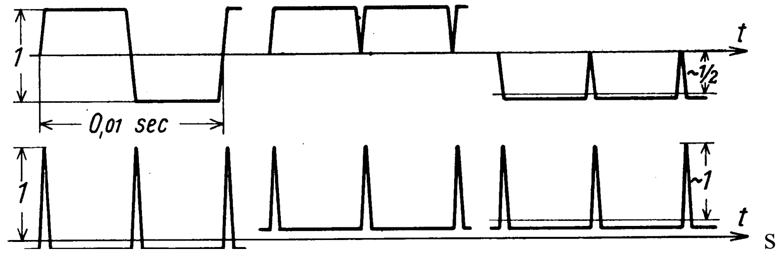


Fig. 21 The effect of polarity-reversal.

Fig. 21 describes this: To the left, two equally intense pressure curves are shown as required by the area formula (2). They may come to the first rectifier in this form (neglecting the filter.) Just to the right, the same curve is shown as it would look after an ideal full-wave rectifier. In the case of the upper curve of Fig. 21, we have a case where the triode would display almost nothing, because the direct current component would be so great. In the third series, the same curves are shown after the polarity-reversing device. One will indeed reverse the polarity of first sound because the peak-triode shows more (~1/2); the second curve is not polarity-reversed because the triode shows more (~1). That the excursions for the same loudness differ by about 6 Phon is no error, because in the filter the peaks of the lower curve are weakened more than those of the upper curve by about the same amount (cf. Fig. 20 and the explanation there.) Again, the upper (trapezoidal) curve does not come through the filter so sharp-edged (especially if it doesn't stay so long at the same amplitude,) so the polarity reversal is really not as important as it appears in the example. A trial with a flat-topped curve form without polarity reversal resulted in an indication about 10 Phon too low, while with the polarity reversal it indicated the right value. For practically all noises encountered, one can allow *U* to stay in the same place, for a pressure curve of the upper sort in Fig. 21 is seldom encountered. One almost always has to deal with short-lasting high or low pressure peaks (motorcycles.)

The objective sound measurer should be equipped with a potentiometer that is always set for the same excursion of the indicating instrument, so that the triode can be more easily calibrated [dimensioned?]. Thus one can read off the measured loudness on the potentiometer. All the sounds of Fig. 24 should be tried for the calibration of the potentiometer. The result is, as Figs. 2 and 3 already show, that the loudness scale of the 1000 Hz tone remains perfectly correct in the range from 50 to 100 Phon. Fig. 22 shows, as an example, the values measured by four persons for a buzzing tone of the type in Fig. 23 *a*.

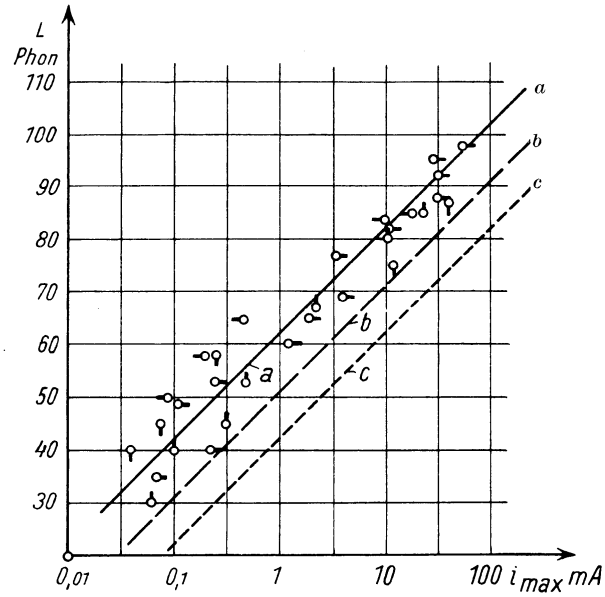


Fig. 22 The dependence on i_{max} of the loudness of a buzzing sound in the free dynamic telephone. *a* Display of the objective apparatus. *b* Single peak registering full-wave rectification. *c* Effective value registering.

The output of the new objective apparatus is displayed at the same time, one with synchronized peak-triode and another such with effective value recording. It clearly appears that the logarithmic rule applies so exactly in this range of loudness (50 to 100 Phon.) that with a reference loudness of 70 Phon, even with a 100 Hz tone, the error is still not greater than 6 Phon. ([2], p.162). On the high side, the loudness scale remains practically constant even to 10,000 Hz. In any case, below 40 Phon *L* one obtains, with many noises, great deviations from the logarithmic loudness scale (cf. Fig. 2). The loudness decreases more rapidly than the corresponding voltage. Therefore the apparatus should be used only for sound intensities of 50 to 100 Phon., in particular, these are the most practically important. The potentiometer could thus be calibrated with 20 Phon. for respective voltage factors of ten; it could be used once for rough and once for fine adjustment.

The *filter* would simulate the ear-sensitivity curve at 70 Phon. It should be built with constant characteristic impedance from [Translator's Note: Brücken-*T*-Glieder [30] – possibly unbalanced attenuation networks?] and so calculated that the damping of the microphone and its input and output transformers together produce the correct ear-damping curve. The greatest run-time difference rises to1.25 msec. for which, in any case, the greatest attenuation lies below 400 Hz. Nevertheless, this must be the upper limit of the phase distortion.

For the peak-triode one can possibly change the following values:

1. Capacitor *C*
2. Output Resistance *R*,
3. Input Resistance R_e,
4. Response time of the indicating instrument.

The response time of the apparatus for short impulses is determined by the time constant *CR* and the period of the instrument. The recovery time will usually be determined simply by that of the instrument itself. By increasing *C* one can obtain a reduced excursion for very short-lasting impulses; the capacitor doesn't fully charge. One can achieve the same result by increasing the input resistance R_e without changing the time constant CR. The capacitor C must be charged by the grid current, which is limited by the rectified voltage on R_e. If very short-lasting peaks are still not displayed correctly, as is here the case, then one may not make R_e too large, while R can be 1000-fold greater.

The response time of the instrument should be large, if possible, for convenience in reading it. Practically, however, one soon reaches a limit to this, since because of the necessity for a full indication of short-lasting impulses, CR must be made very large. However, this is not possible because of the time-integration of the ear we discussed. (cf. Fig. 10). Besides, the ever present ion stream would soon set a limit (in the instrument it was at most $5x10^{-10}$ A.) Again, C must be small so that the capacitor will still fully charge as in Fig. 1 with $T = 1$ msec. Within certain limits one can also regulate this with the amplitude adjustment, for one has control of the grid current. According to the above, one should make this amplitude as large as possible, as long as no rectification by the anode occurs. In practice, it is not at all possible to fully satisfy all factors. An instrument was chosen with a small rise-time (with a current curve like Fig. 1, it fully deflects in $T = 360$ msec.) on which a reading could still be made comfortably. The curves of Fig. 10 were then reproduced approximately correctly.

The sizing of C, R, and R_e is fully determined through the initial descriptive measurements of clicks. It can be found empirically. The best was found to be, for a grid current of $5x10^{-6}$ Amp. at 0 Volts and a constant peak adjustment of the grid of 2 Volt maximum, $C = 500$ cm. [ranslator's note – cm., not μF?], $R = 10$ Megohm, and $R_e = 5000$ Ohm. A strict adherence to these values is not necessary. The base of the tube must be well isolated because of the high output impedance. A reduction of R in using an indicator instrument with normal rise time is not achievable by normal technical means. The adjustment of the grid and the anode voltage cannot be too small, because otherwise the ion stream rather than CR determines the time constant.

The noises of Fig. 2 (curve *b*), 3 (*X*s), 9 (crosses), 10 (crosses), and 22 (line *a*) were measured with the instrument described and the values entered there. The measurements were done over the dynamic telephone; upon consideration of the volume conditions, its condenser microphone was pressurized to one atmosphere and hermetically sealed, [Translator's note – This is a difficult sentence to read literally but I think I got the gist of it.] Since the sharp clicks contain all frequencies, even very short waves (up to ultra-short), great care was taken to provide good static shielding of the microphone. Otherwise the click, as an impulse rectified in the first tube, will be transferred by electrical means in addition to the acoustic path. In any case, the calibration of the apparatus was made using the dynamic telephone of Siemens & Halske with a pure tone of 1000 Hz. Even so, the air-volume content for the Barkhausen-Noise-gauge's objective was repeatedly recalibrated upon reflection, because it had shown that it could change by about 5 Phon.

Now very extensive measurements were made to determine the practical usefulness [Translator's note – I believe the author made a typo and spelled Brauchbarkeit as Baruchbarkeit] of the developed apparatus. In all 17 persons took part in the measurements. The main point of these measurements was a general adjustment to reality. Fig. 23 shows, by means of a measurement made in a normal room, that this criterion is not satisfied: the same buzz-tone was viewed with a cathode-ray tube oscilloscope first directly (*a*) then over a loudspeaker and microphone, 2 m. apart in a highly damped room (*b*) and finally just in an ordinary room (*c*)

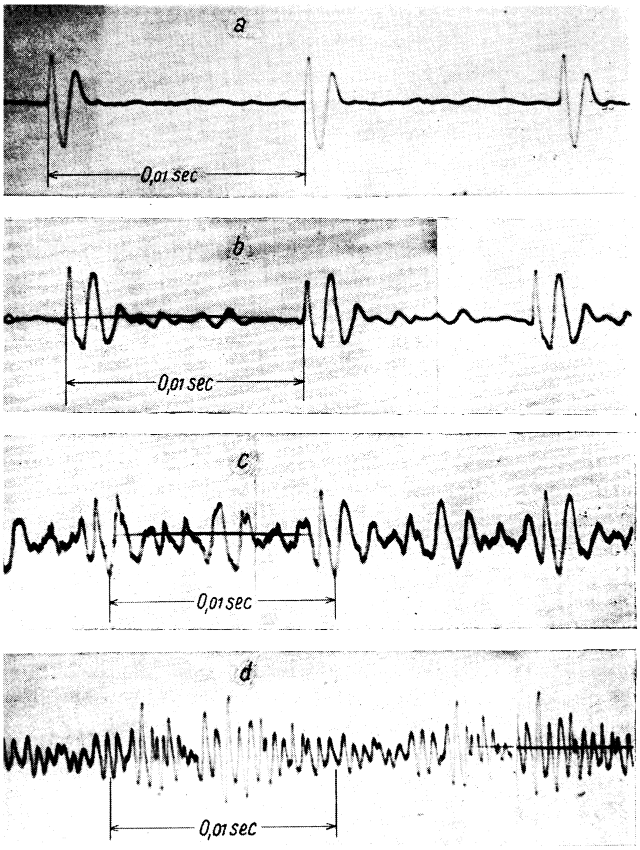


Fig. 23 *a* Buzz. *b* The same over an acoustic transmission path of 2 m. in a damped room. *c* Same as *b*, only in an undamped (normal) room. *d* Noise 6 in Fig. 24.

The buzz greatly loses its noise-like character due to the room acoustics. The ratio between the peak value and the effective value is much smaller. It is therefore necessary to make most of the measurements in a damped room, for that is a much harder test and corresponds to reality for loudness measurement, which indeed will preferably be applied in the open. The noises themselves would most likely be remotely related to reality. In Fig. 24 they are shown as they are sensed by the ear.

Fig. 24 Measurement of Noises

a Subjective Measurement. Mean value, always for about 9 persons

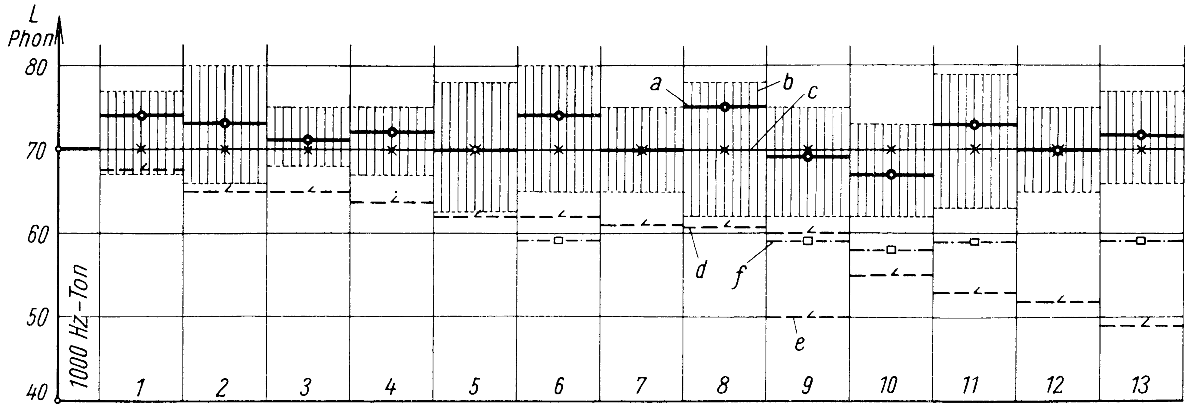
b Range of scatter of the subjective measurement

c Objective measurement with the new apparatus

d Effective value measurement

e Effective value in the open (dynamic telephone)

f Push-pull peakmeasurement (CR = 0.1 sec.)



Noises

1 Hiss. 2 Circular saw.
3 Orchestra music.
4 Noise 10 in a damped room.
5 Sizzle. 6 According to image 23*d.*
7 Buzz tone, damped.
8 Motorcycle in the distance.
9 Buzz tone, image 23*a*.
10 Mortorcycle, 50 Hz.
11 Iron hammer 7 Hz.
12 Wooden hammer 4 Hz.
13 Click (Fig. 1) 20 Hz.

The measurements were done by a person measuring with the Barkhausen noise meter 4m. from the noise source and close to the condenser microphone. At the same time, the loudness in the next room was measured objectively. In the measurement room, there stood only the microphone of the objective apparatus with a single stage amplifier, which proved necessary because of the long connecting leads. Simultaneously, each time, the effective value of the voltage after the filter was measured in order to investigate how it behaved in that sort of apparatus. (Later such apparatuses were repeatedly built.) The effective value measurements were taken through an especially frequency-independent amplifier with a detector the indication of which, for a developing pressure curve, was checked and corrected with a thermogalvanometer.

For all these noise measurements, the loudness was kept in the range of 50 to 100 Phon. In Fig. 24 the clarity [? *Übersichtlichkeit*] half [6]of all measurements were reduced to a 70 Phon indication on the objective apparatus. I was reduced to that because, even with no noise, upon the investigation of the noise intensity scale an exact deflection on the scale of a 1000 Hz tone was shown. For other sound intensities in the chosen domain, therefore, Fig. 24 should be specifically consulted. As an example, the investigative protocol for noise 9 is reproduced in the following table.

Measuring Person	New objective loudness measurer	Effective value measure	Subjective Measure	*S* red. to 70 Phon 0	Average of R	Scatter Range
P	*O* Phon	*E* Phon	*S* Phon	*R* Phon	Phon	Phon
1	52	43	50	68		
2	52	43	50 - 55	70.5		
3	56	47	55 - 60	71.5		
4	66	56	65 - 70	71.5		
5	72	62	65	63		
6	72	62	70 - 75	70.5		
7	75	65	80	75	69	62 - 75
2	78	68	75 - 80	69.5		
1	78	68	75	67		
8	78	68	70	62		
9	80	70	85	75		
2	82	72	80 - 85	70.5		
1	93	82	90	67		
4	93	82	90	67		

The results are arranged in Fig. 24. One sees the great error that the instruments which indicate effective value make for noises containing peaks. The settling time of the of the measuring instrument only becomes a consideration for the noises 11 and 12. A useable indication from an apparatus measuring effective value could only be obtained with an instrument rise time of 10^{-2} sec. (Oscilloscope) and greater damping. The false indications from an effective value measurement can be quite drastic, for instance if the buzz tone of Fig. 23*a* is produced on the dynamic telephone, first directly and then through the chosen filter.

[6] Translators note: I am tempted to translate *Übersichtlichkeit halber* as the mean value, since that would make sense in context.

Both times, the effective value is exactly the same, while the objective apparatus shows a 7.5 Phon difference, which exactly expresses the subjective feeling. With a longer filter chain, the difference may become greater.

Numerous measurements were carried out with a normal peak-measuring instrument with a push-pull triode and 0.1 sec. time constant in the *CR* branch. The measured values are entered in Fig. 24. For noises containing peaks, they lie about 12 Phon below the value of the new apparatus, as the theoretical treatment requires. The bounds of the scattering range were exceeded, for the most part. Because noises containing strong peaks are the most practical to measure, one could make this apparatus of limited utility by an intentionally false calibration. This appears already to have happened several times.

Because very extreme noises are investigated among others, on the basis of the test results it can be said that the described apparatus is thoroughly usable in practice. Indeed, a single click of the Fig. 1 type was still indicated about right. In any case, because of the singular form of the curves in Fig. 10, which was previously noted, a little inexactness on either side is unavoidable in the transition from noise to a single click because of the limits of adjustability of the triode. This imprecision of the correct indication of noise became more pronounced because of the full-wave rectification. Because the single click itself does not have such an exactly defined loudness, this is more important (cf. Fig. 2).

For several noises that were produced over a loudspeaker by a voltage source, it was also possible to repeat the measurement, at least up to frequencies of about 3000 Hz, in completely free space by producing them through the dynamic telephone, closely pressed to the microphone, instead of on the loudspeaker. In these measurements the new objective apparatus still showed completely correct results, while the indication of the effective value was even more unfavorable (cf. Fig. 24 Noise 9). In reality, one will mostly need to deal with an intermediate condition between these extremes (free space and undamped room.) However it is important to confirm that the measurements give the right value in a simulation of free space, for naturally the sound absorption of the damped room is frequency dependent (but the high frequencies are essentially not reflected at all.)

It must also be mentioned that all the subjective measurements of noise intensity (and also the calibration) were made binaurally: i.e. the sound to be measured encountered the one and the comparison tone the other with good air-termination. Thus, since only a single method of measurement was used, the correctness of the apparatus cannot be impugned by the fact that people hear differently with both ears than the do with one.

It is interesting that a feeling for loudness can be practiced just like "absolute pitch" for the frequency of a note. According to many measurements, I can name quite accurately the intensity of a sound precisely to within 5 Phon without making any comparison.

The principle of full-wave, or yet more frequent[7], rectification, in conjunction with an appropriate filter may probably be applied advantageously to the measurement of annoyance. It is known, indeed, that noises containing strong peaks act very disturbingly on the human organism, and those would be strongly emphasized by repeated rectification.

[7] Translator's note – I presume he is referring to the squaring after full-wave rectification noted previously.

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Summary

I. 1. The dependence of the loudness of various sorts of clicks and duration was investigated. A new loudness formula was presented for the determination of their sound- intensity from their given pressure curve. It indicated that an impulse, the maximal pressure integral over a time of 0.3 msec. yielded a factor responsible for the loudness. On the basis of loudness measurements of sounds that steadily progressed from single clicks to noises and to tones, a principle was formulated with the help of which the loudness formula could be generalized to arbitrary sounds. The loudness values of clicks, noises, and tones computed according to the formula agree well with the measured values.

2. The decay of loudness after cessation of a tone or noise was investigated by a covering method. It takes place on the general order of 0.5 sec. At the end of first section, the sound reception through the ear was briefly discussed from a physiological point of view.

II. In the second section a newly developed objective apparatus for the measurement of loudness was described. It works through multiple rectification and recording of peak values. The proper values for the individual parts were derived, on the basis of numerous loudness measurements of clicks and noises, by many persons. It showed that the loudness scale of all (in part very extreme) investigators, comparing noises with good accuracy against a 1000 Hz tone was in the range of 50 to 100 Phon. Many measurements that generally conformed to reality were made in order to check the practical utility of the new objective apparatus, for instance, by the use of a damped room to compare with the measurement in the open. It appeared that the apparatus gave completely satisfactory results for sound-intensities that were very near the mean value of the subjective measurements and always within the range of their distribution. Finally, the usefulness of other previously used loudness measurers were tested.

Literature

Foundations

1. H. v. Helmholtz, Lehre von den Tonempfindungen. Braunschweig 1863. — 2. H. Fletcher, Speech and Hearing. New York 1930. — 3. G. v. Bekesy, Zur Theorie des Hörens. Phys. Z. **30**, 115–125 und 721–745, 1929, Annalen d. Phys. (5) **13**, 120, 1932 und (5) **14**, 111, 1932.

Sound Measurement

4. H. Barkhausen, Ein neuer Schallmesser für die Praxis. Z. Techn. Phys. **7**, 599, 1926, Z. V. D. I. **71**, 1471, 1927. — 5. G. Bakos u. S. Kagan, Lärmmessung. Z. V. D. I. **76**, 145, 1932. — 6. E. Meyer u. C. Willms, Geräuschmessungen an Kraftfahrzeugen. Z. V. D. I. **76**, 983, 1932. — 7. R. H. Galt, Results of Noise Surveys. Journ. Ac. Soc. Am. **2**, 530, 1930. — 8. T. G. Castner, A Portable Sound Meter. Bell Lab. Record **10**, 334, 1932. — 8a) T. G. Castner, E. Dietze, G. T. Staution u. R. S. Tucker, Indicating Meter for Measurement and Analysis of noise. Bell Telephone System technical publications B 563 (1930). Journ. Am. Instit. Electr. Eng. **50**, 342, 1931. 9. J. Obota, S. Morita, On the accuracy of the aural method of measuring noises. Journ. Ac. Soc. Am. **4**, 129, 1932.

Frequency and amplitude

10. J. Tröger, Die Schallaufnahme durch das äußere Ohr. Phys. Z. **31**, 26–47, 1930. — 11. B. A. Kingsbury, A Direct Comparison of the Loudness of Pure Tones. Phys. Rev. **29**, 518, 1926 und **29**, 588, 1927. — 12. B. Shower u. W. Biddulph, Differential Pitch Sensitivity of the Ear. Journ. Ac. Soc. Am. **3**, 275, 1931. — 13. R. L. Wegel, C. E. Lane, Auditory Masking of one Pure Tone by another. Phys. Rev. **23**, 266, 1924. — 14. R. R. Riesz, Differential Intensity Sensitivity of the Ear for Pure Tones. Phys. Rev. **31**, 867, 1928. — 15. T. Ham, T. Parkinson, Loudness and Intensity Relations. Journ. Ac. Soc. Am. **3**, 511, 1932.

Sensing of Noise Amplitude

16. H. Fletcher, A Space-Time-Pattern Theory of Hearing. Journ. Ac. Soc. Am. **1**, 311, 1930. — 17. H. Barkhausen, G. Lewicki, Die Empfindlichkeit des Ohres für nicht sinusförmige Töne. Phys. Z. **25**, 537, 1924. — 18. H. Barkhausen, H. Tischner, Die Lautstärke von zusammengesetzten Tönen und Geräuschen. Z. Techn. Phys. **8**, 215, 1927. — 19. F. A. Firestone, Binaural localization of pure tones. Journ. Ac. Soc. Am. **2**, 260 und 271, 1930. — 20. H. Fletcher, J. C. Steinberg, Dependence of Loudness of a Complex Sound. Phys. Rev. **24**, 306, 1924. — 21. G. W. Stewart, Binaural Hearing. Journ. Ac. Soc. Am. **1**, 344, 1930. — 22. R. L. Wegel, Physical Data and Physiology of Excitation of the Auditory Nerve. Annals of Otology **41**, 740, 1932. — 23. H. H. Heinze, Diplomarbeit. Dresden 1932.

Sound Spectra

24. H. Fletcher, Some Physical Characteristics of Speech and Music. Bell Syst. Techn. Journ. **10**, 349, 1932. — 25. H. Lueder, Zur Statistik der Intensitätsverteilung im Spektrum natürlicher Klangbilder. Wiss. Veröff. Siemens-Konzern **9**, 167, 1930. — 26. E. Meyer, Klangspektren von Musikinstrumenten. Z. Techn. Phys. **12**, 606, 1931. — 27. U. Schmidt, Auspuffgeräusch von Verbrennungsmotoren. Dissertation. Charlottenburg 1932. — 28. L. J. Sivian, H. K. Dunn, S. D. White, Absolute Amplitudes and Spektra of Certain Musical Instruments ... Journ. Ac. Soc. Am. **2**, 331, 1931.

Four-pole Networks

29. K. Küpfmüller, Die Erhöhung der Reichweite von Pupinleitungen. El. Nachr. Techn. **3**, 82, 1926. — 30. V. Gandtner, G. Wohlgemuth, Diagramme zur Berechnung von Vierpolen. Wiss. Veröff. Siemens-Konzern **7**, 67, 1928. — 31. S. P. Mead, Phase Distortion and Phase Distortion Correction. Bell Syst. Techn. Journ. **7**, 195, 1928.

Peak Audion

32. D. Thierbach, Impulsmesser. Z. Techn. Phys. **9**, 438, 1928. — 33. W. Grube, Impulsverlängerung. Dissertation. Charlottenburg 1930. — 34. G. Lubszynsky, H. Weigt, Aussteuerungsgeräte im Rundfunkbetrieb. El. Nachr. Techn. **9**, 4, 1932.

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