CALCULATING ANNOYANCE AND SOUND QUALITY WITH A DIGITAL MEASUREMENT SYSTEM BASED ON SIGNAL PROCESSORS

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To scale a signals's sound quality (annoyance) it is necessary to consider not only loudness but also sharpness, roughness, fluctuation strength and pitch strength (Zwicker, Internoise '89).

Loudness has been standardised in DIN 45631 and ISO 532 B. Loudness data are superior to dB(A)-values, when hearing based sensations have to be scaled. Psychoacoustic research work during the last years delivered additional results and models for other psychoacoustic parameters. Now a psychoacoustic analyser based on digital signal processors is available, which can calculate these values in realtime. Two different ways for combining psychoacoustic values to a global parameter are possible: calculation of the unbiased annoyance in accordance with Zwicker, or calculation of a sound quality index with an userdefined weighting function. The latter is recommended when a product related sound quality has to be designed.

Physical quantities such as pressure, power, or velocity can be defined and measured without regard to their effects on man. These are referred to as objective quantities. On the other hand, there are also subjective quantities such as loudness or comfort that are ascertained through human perception. It is these quantities which occur in psycho-acoustic experiments. It is only coincidental when objective quantities (i.e. acoustic power) of two sound signals have the same relation as subjective quantities (i.e. loudness). Ordinarily, the acoustic power must not only be doubled, but, in fact, be increased by a factor of 10 in order to double the "loudness". The inverse of this is also applicable: a reduction of the acoustic power by half will not half the perception of "loudness".

In acoustics, the most important objective sound field quantities are sound pressure and particle velocity. The product of sound pressure and particle velocity is the sound intensity, a value which may be measured in scalar and, as of recently, vector form. By multiplying the intensity with the area, the acoustic power is obtained. In psycho-acoustics, one speaks of Loudness (N), implying the value that describes a perception of loudness. Loudness is no way comparable to the objective quantities of sound pressure, acoustic power, or acoustic intensity.

Human hearing has a varying sensitivity to sounds in different frequency ranges; high tones (10 kHz) or low tones (100Hz) are less perceptible than tones with a frequency of, for example, 3 kHz that occur at the same level. In order to take this bandpass characteristic into account, a weighting filter was standardised: the A-weighting filter. When measuring sound pressure level through an A-filter, the level is then referred to as the A-level in dB(A).

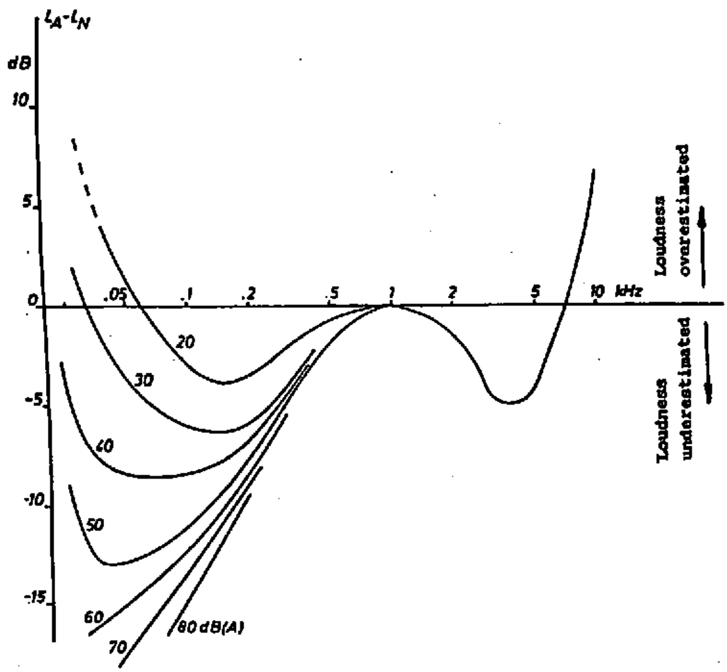


Figure 1: Measurement error from application of the dB(A) measurement to the loudness of small-band sounds.
L_A = A-level of the sound
L_N = A-level of an equally loud 1-kHz tone

	Small-band Sounds			Broad-band Sounds
Center frequency	30-1000 Hz	100-300 Hz	>300 Hz	
A-level				
40-60 dB(A)	7	8,5	10	9
>60 dB(A)	8	9	10	12

Table1: Essential reduction of the A-level in order to a halving of the loudness.
Assumption: Frequency independent attentuation.

It may be asked if sine-tones of different frequencies but similar A-levels have the same loudness: The answer is no. A 4-kHz-tone with, for example, an A-level 60 dB(A) is louder than a 60 dB(A), 1-kHz-tone. In order for them to have the same loudness, the level of the 4-kHz-tone must be lowered to 55 dB(A) (Note that it is db(A), not dB). Sine tones with equal loudness may differ by as much as 13 dB(A). Figure 1 indicates deviations from loudness perception.

Even more complicated are the relationships between broad-band sounds . Pink noise at 50 dB(A) is 4 times as loud as a 1-kHz-tone (or respectively a 1-kHz third-octave noise) at 50 dB(A). A 1-kHz-tone at 70 dB(A) is only half as loud as a pink noise at 61 dB(A), despite a higher sound pressure level (9 dB(A)) and an A-weighted acoustic power that is 8 times as large. Generally speaking, broad-band sounds are louder than narrow-band sounds, despite the fact that they may have identical A-levels.

A reduction in acoustic power may or may not result in the reduction of loudness. As long as only the level of a noise changes, and its spectral composition will remain the same, the following approximations can be made: A halving of the sound's loudness will result, when the A-level is reduced by the respective values listed in Table 1. Table 1 applies only for cases in which all of the spectral lines for a sound are altered by the same dB sum. If on the other hand, the spectral composition of the sound is modified, a reduction of the A-level and an increase in loudness is obtained. At the Technical University of Munich, the Institute of Electro-Acoustics performed experiments measuring the noise produced by a motorbike before and after noise-damping modifications were implemented. Although modifications caused the A-level to be reduced by 3 dB, the loudness was raised by 50 %.

Noise abatement often is a synonym for loudness reduction. But it should also be kept in mind, that annoyance and loudness are different quantities. "Unbiased annoyance" is defined as the response of subjects being annoyed exclusively by sound under describable acoustical circumstances in laboratory conditions without relation to the nature of the sound source. Zwicker publised a proposal for defining and calculation the unbiased annoyance (Internoise 1989). Additional research work showed that loudness is the most important factor of unbiased annoyance, but sharpness, fluctuation strength, roughness and pitch strength also have to be considered. Roughness and pitch strength seem to play a more important role than Zwicker assumed.

When a subject's attitude towards a sound has to be considered, the term "sound quality" instead of "biased annoyance" is used. To the driver of a sportscar the engine's sound may have no annoyance at all, although there is plenty of roughness and loudness. The goal of psychoacoustics is to weight individually each sensation parameter, and sum all these values together. The result will define the sound quality. The individual quantities are supposed to be independent of each other (orthogonal), but loudness plays a dominant role: If a signal's loudness is reduced to zero, all the other psychoacoustic quantities become unimportant. There are many sound sources, whose loudness ought to be reduced to zero: we may not want to be informed about an air conditioner's efficiency by the emitted amount of acoustic sound power; we can feel if the machine is working or not. A cassette-tape-recorder's motor should be as quiet as possible, because it is not the motor's sound that is supposed to be recorded. But there are also sound signals that carry information, and these signals must not be canceled. If a car's engine were inaudible, we would have no feedback of rotational speed and mechanical loading. Especially for a hand-operated gear-box this feedback is necessary. A car's fan should be inaudible, the flashing of the direction indicator should not. The honk - of course - should not be inaudible; to gain maximum attention, loudness, roughness and (in some cases, e.g. Kojak) fluctuation strength have to be high.

No general guide lines can be given for the weighted summation of psychoacoustic quantities. Even in the automotive industry different weighting functions occur. A sport's car has to have a different sound than a big limousine. It is the manufacturer who sets standards for the sound quality of his products. It is the customer who decides whether to buy or not.

Psychoacoustic quantities can be measured by signal processor based analysers. The most important quantity is loudness, which has to be calculated not only as a total value but also as a spectral distribution with a time resolution of 2 ms. Temporal masking has to be considered as well as spectral masking. Masking means that a signal's component becomes inaudible, when masked by another component. Low frequencies at high levels will mask for instance high frequencies at low levels. (Temporally) leading signals mask their followers. Sharpness is (somehow approximated) the x-axis of the loudness spectrum's centroid. Signals with dominating high frequencies yield high sharpness, signals with dominating low frequencies low sharpness. Roughness and fluctuation strength are related to the temporary deviation of the loudness spectrum. Modulation frequencies between 1 Hz and 10 Hz are responsible for fluctuation strength, modulation frequencies between 10 Hz and 100 Hz produce roughness. Pitch strength depends both on spectral shape and modulations. A pure tone has a pitch strength of 100 %, broadband noise has almost no pitch strength.

The following figures show psychoacoustic results concerning different automotive engines.

Fig. 2 shows a roughness spectrum for pink noise. The (frequency-) specific roughness is depicted in the frequency range between 224Hz and 12.5kHz, the right column depicts the total roughness divided by 10 (a scaled summation of all specific roughnesses). The roughness spectrum looks similar to a third octave spectrum, but means something different. If the level of the pink noise would be increased, all third octave band levels would grow, too. The roughness spectrum would remain almost constant.

Fig. 3 depicts the roughness spectrum of a 12-cylinder-engine at idle. The upper frequency range is emphasized, which means that higher frequencies are modulated more than lower frequencies. The sound is described as being twittering. Fig. 4 belongs to a 6-cylinder-engine at idle at nominal temperature. Significant differences can be seen in comparison with the 12-cylinder-engine and pink noise respectively. The maximum at 1000Hz is characteristic for petrol engines. Fig. 5 depicts the roughness spectrum of the same engine at low temperatures. Roughness increased significantly in the upper frequency range. In Fig. 6 a (warm) engine with a poor sound quality is shown: the driver complained of sizzling noise.

Fig. 7 and 8 show the roughness spectrum of a diesel-engine, with normal temperature (Fig. 7) and low temperature (Fig. 8). Even with normal temperature the roughness is much greater than that of the 12-cylinder-engine. Things become worse at low temperatures. The typical knock of the diesel-engine is characterised by a strong roughness between 1000 and 3150Hz. The total roughness exeeds that of the 12-cylinder-engine by a factor of 3. The engine Fig. 9 has been rejected due to rumbling and clicking interference noise.

Fig. 2: Pink noise:

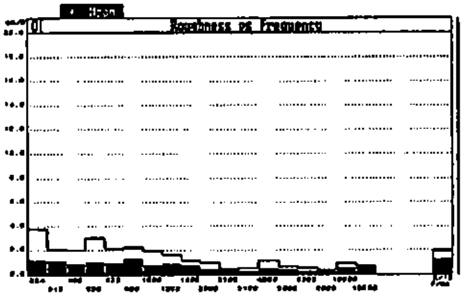
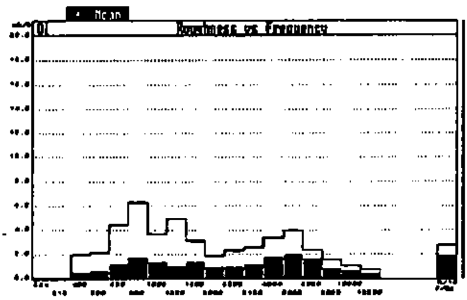


Fig. 2-9:
Roughness and fluctuation strength spectra for several engines.

Fig. 3: 12-cylinder engine:



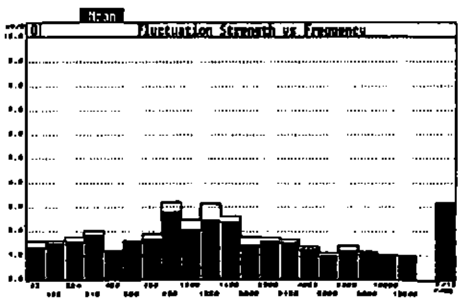
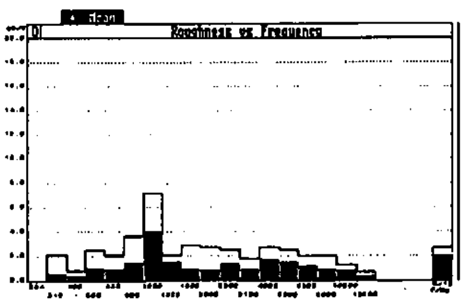


Fig. 4: Petrol engine (warm):



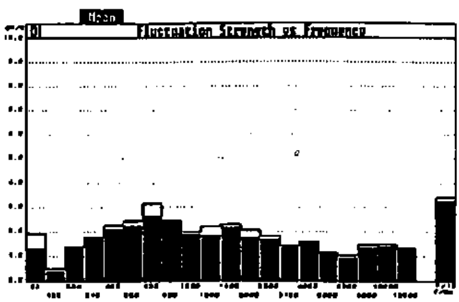


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Fig. 5: Petrol engine (cold):

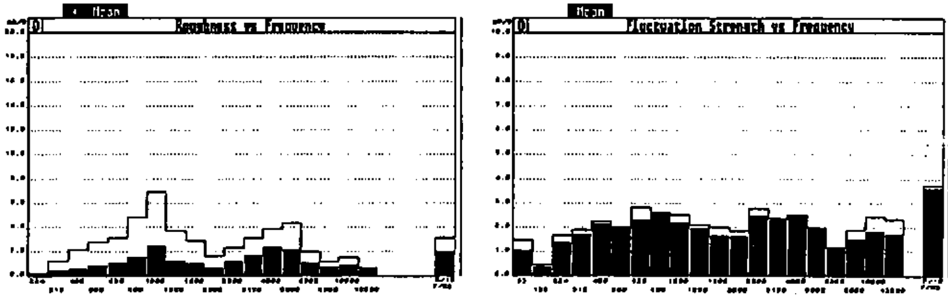

Fig. 6: Petrol engine, sizzling:

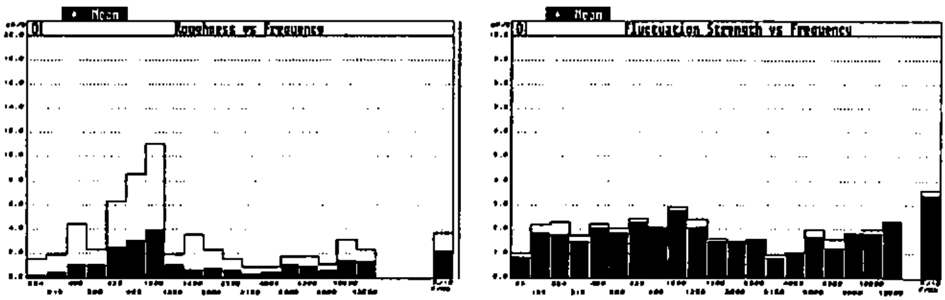

Fig. 7: Diesel engine (warm):

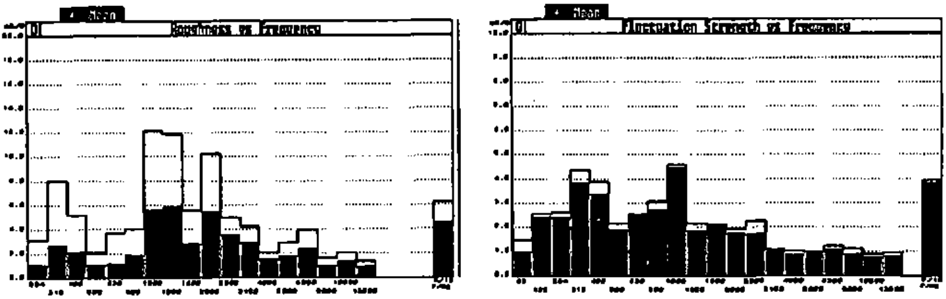

Fig. 8: Diesel engine (cold):

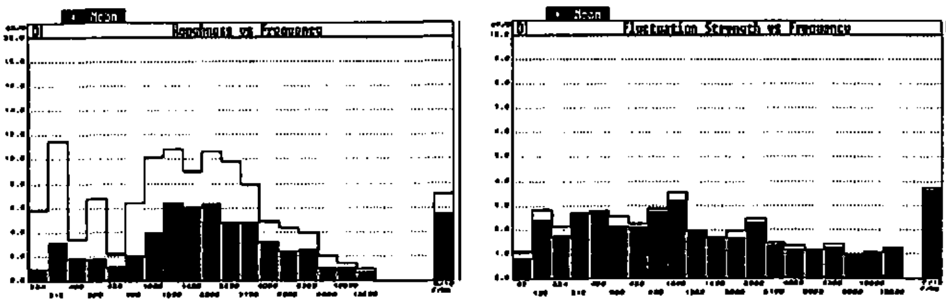

Fig. 9: Diesel eng.
, rumbling and clicking: