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Instrumentation for Sound Quality Evaluation

Markus Bodden
Ingenieurbüro Dr. Bodden, Herthastr. 29, D-45131 Essen, Germany

Summary
As a result of psychoacoustic research, a set of psychoacoustic indices has been developed which allow for an instrumental prediction of attributes of hearing events. These indices offer - in combination with acoustic workstations for aurally-adequate sound recording, standard signal analysis and signal modification - powerful tools for the assessment, evaluation, and improvement of sounds. Nevertheless, a closer look to the instrumentally calculated measures shows that the current technique still is far from simulating human sound perception and evaluation in all its facets. They have to be more regarded as tools to evaluate specific features of sounds, and less to give a global and final evaluation result. Thus the user of instrumental methods has to be aware of the meaning of all the indices from both, the psychoacoustical and the instrumental point of view - he has to have the corresponding expertise. It is not the intention of this article to recommend one of the tools for sound quality evaluation which are available on the market. The comparison shows that the systems have different philosophies with regard to their hard- and software basis, so that the appropriate system for each user has to be selected according to his specific requirements, his working environment, and personal preferences.
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1. Introduction

Whenever we listen to a sound, we get - at least subconsciously - an impression about its sound-quality, as illustrated on the right side of Figure 1. This is of particular interest for manufacturers of products which emit sound - whenever the product is used, its sound is judged by the user and other persons receiving the sound.

In contrast to this human evaluation instrumentation tools (left side in Figure 1) are commonly used in various fields since they offer advantages from an engineering point of view:

- instrumentation methods can be standardized and results thus directly compared;
- instrumentation methods lead to reproducible results (if all parameters and the influencing factors are held constant);

It is thus not surprising that there is a strong demand for instrumentation tools for sound quality evaluation, too. In contrast to the "standard instrumentation", as shown on the left in Figure 1, this instrumentation requires a closer link to the user, as depicted on the bottom of the figure.

The development of such instrumentation has to cope with a variety of difficulties. The problem starts with the definition of the term "sound quality" - it is often interpreted in different ways. It is obvious that different interpretations of sound quality lead to different methods for the evaluation of sound quality. According to that the task to evaluate sound quality is not even yet clearly defined for methods using tests with subjects. The contributions of Blauert & Jekosch [1], Fastl [2], and Guski [3] (all in this issue) demonstrate that this task is influenced by a variety of physical, psychoacoustic, and psychological factors. As a consequence it seems to be impossible to define a common and global method for the evaluation of sound quality which can be applied to any existing sound.

The latter point directly rises the following questions:

- Can instrumental methods be used at all to evaluate sound quality (regarded from a theoretical point of view)?
- If yes, to what extend?
- What methods and tools do exist today?
- What has to be considered in applying these methods, what are the restrictions, limitations?
- What are the riscs and dangers in applying them?
- What evaluation tools can be expected to be available in future?

It is the intention of this article to discuss these problems.

2. Sound-Quality Evaluation and Instrumentation: a contradiction?

The basics of sound quality evaluation are discussed in detail in the contributions of Blauert & Jekosch, Fastl, and Guski in the same issue, so that only aspects relevant to instrumentation should be pointed out here again.

General problems which hinder a definition of a general method to evaluate sound quality are:

- Cognitive influences: factors related to the sound source (e.g., the image of the source, whether it is a sports car or a family car), factors related to the situation in which the product emitting the sound is used (e.g., interaction with the source, we expect an acoustical reaction if we accelerate a car), and factors related to the person using the product (e.g., expectation) influence the evaluation;
- Multidimensionality: the perception of sound is based on a set of different dimensions describing different features of the perceived sound. The dimensions can be grouped

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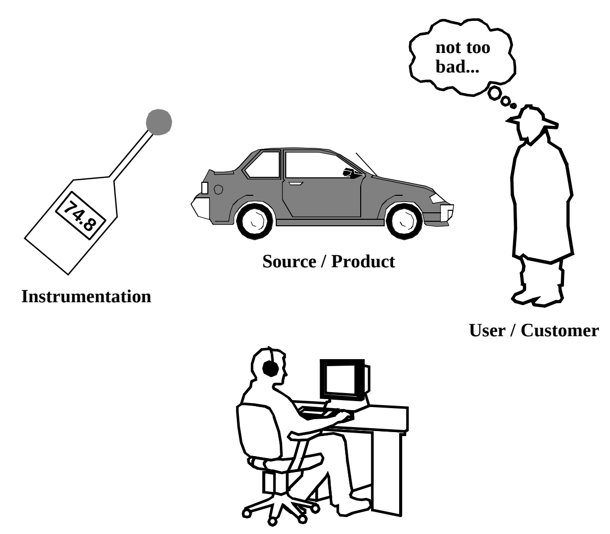

Figure 1. Sound-quality evaluation by humans (right), standard instrumentation (left), and instrumentation for sound-quality evaluation (bottom).

into *physical*, *psychoacoustical*, and *psychological* factors. Anyhow, humans just select 3-4 dimensions out of this pool for an evaluation. The selection and weighting of the used dimensions is individual and influenced by cognition.

This shows that it might be possible to define methods which can be used to quantify specific dimensions and to account for cognitive factors, but it is hard or even impossible to set up a general rule about which dimensions are selected and how they are combined to set up the final evaluation judgement.

In contrast to that such a model appears to be realistic for specific and well-defined tasks, e.g., the evaluation of a specific type of noise in a specific situation. An approach like this aims at keeping constant all non-acoustic factors which influence the decision, so that differences in the evaluation result are purely due to acoustic features.

Instrumentation methods have to cope with the same basic problems as the evaluation by humans. But, in order to build a general instrumental evaluation method, the pre-requisite would be to have instrumental methods which are able to quantify all relevant influencing factors. It is obvious that we are far away from that status. Thus we have to be aware that instrumental methods have limits and restrictions.

However, especially engineers like to have instrumental methods at their hand which they can apply to their problems. It seems to be a general trend that people tend to “believe” more in the results of instrumental measurements than in results of psychoacoustical measurements. One reason to explain this behaviour is that the reliability of psychoacoustical results is often underestimated due to a lack of knowledge about psychoacoustical methodologies.

As a consequence, psychoacoustical results are often referred to as not being objective, while instrumental measurements are considered as always being objective. But, objectivity is given if the statistical distribution of the sound evaluation results of different subjects is equal and thus independent on the individual subject [4]. Psychoacoustical results are thus also objective if these requirements are met. In this context it also has to be considered that the instrumental indices usually have been developed based on results of psychoacoustical investigations. Thus they offer the same restrictions with regard to a generalization as the underlying psychoacoustical results.

The general danger of instrumental indices is that their restrictions are neglected - they are considered as being general. In consequence it is a crucial prerequisite that the user of instrumental indices is aware of the background, the restrictions, and the applicability of the method.

In the following paragraphs several aspects of instrumentation for sound quality evaluation will be discussed in detail. The presentation will start with the interface of analysis tools to physics - the signal acquisition. Then signal analysis methods ranging from traditional measures to psychoacoustical indices will be discussed, the possibilities of signal manipulation tools presented, the aspect of interactivity reviewed, and finally some available tools for sound quality evaluation compared.

3. The Framework: signal acquisition

Before sound can be evaluated, it first has to be picked up. The human auditory system uses two receivers to do so: the left and the right ear. This enables us not only to identify sound sources, but also to localize them in a 3-dimensional space. Compared to the listening with one ear (monaural hearing), the listening with two ears (binaural hearing) gives us a much more precise impression about the surrounding sound field: it is much easier to detect sound sources and to derive further information about them. For an overview on binaural hearing, see Blauert [5].

The historical way to pick up acoustic waves for instrumentation purposes is to take a microphone and to directly connect it to an analogue signal processing tool, e.g., a sound level meter. The principle disadvantage of single-channel recording methods is that they are not aurally-adequate at the very basis - it is not possible to reconstruct the sound field with the correct spatial information. Thus in general single channel recordings are not suitable for sound quality evaluation tasks.

In the course of the development of digital signal processing, todays’ standard is to convert analogue sounds into digital signals and to store them either on a digital tape (DAT), an optical disk (CD-Recorder), or directly on a computer (hard disk or Magneto-optical-disk (MOD)). Simple PC cards offer A/D and D/A converters with sample rates of up to 48 kHz and an accuracy of at least 16 bit. In addition to that, AES-EBU or SP-DIF interfaces are also available which connect computers with DAT-recorders or CD-devices.

An important step towards aurally-adequate sound evaluation was the development of *Binaural Technology* (e.g., see [6]). Motivated by physiology and abilities of the human auditory system, techniques for aurally-adequate sound recording and playback have been proposed. First, the sound at the eardrums was recorded with miniature microphones positioned in the earcanal of a human listener, and played back afterwards via headphones. In the playback situation the listener - under ideal circumstances - should have the same auditory spatial impression as in the original recording situation. See Figure 2 for a schematic illustration.

Thus the spatial information has been preserved by recording the so-called ear signals of the left and right ear. The subsequent step was the measurement of the spatial receiving characteristics of the head: the transfer functions from a location of a sound source to the left and right ear were measured (the so-called Head-Related-Transfer-Functions, HRTFs) and storedin catalogues for a variety of different positions. Then synthetic spatial signals could be created by means of convolving dry signals with the HRFTs corresponding to the desired direction of sound incidence.

The further step was to develop models of a human head, where the eardrums are replaced by microphones. The first models used exact replica of a human head including exact models of the pinna. But, since head geometries are individual anyhow, some dummy heads have abstracted shapes derived from statistical averaged measures. Today several of those dummy heads are available on the market, and although they have different shapes, most of them fulfil the standards like IEC 959 where basic characteristics are defined.

Although dummy heads are a common requisite of noise measurement techniques today, binaural technology still has to cope with a general drawback: interindividuality. Due to different head and torso shapes the binaural receiving characteristics differ to some extend between people. As a consequence an exact reproduction of sound is only possible if the corresponding individual HRTFs have been used during recording. This is possible if in-ear microphones are used, so that the dummy head is replaced by the own head. Corresponding in-ear microphones are also available on the market.

Since a dummy head has a kind of mean HRTFs, some deviations in listening to recordings compared to the original situation may occur: sources which are positioned in front of the head are sometimes localized in the back, and also the distance of sources can be underestimated up to the point that sounds are localized inside of the head. Anyhow, even in the worst case a dummy head recording gives a much better spatial representation than a conventional stereo recording.

A first step to an individual adaptation to a dummy head is the personal equalisation: in addition to the well-known free-field and diffuse field equalisations, some dummy heads offer the possibility to perform an individual equalisation using a digital preamplifier. But, with such a kind of equalisation only the average frequency characteristics can be adapted. The interindividual problem is much more complicated - the equalisation has to be different for each direction of sound incidence. But, this is impossible from a technical point of view because the directions of sound incidence are not directly available in the dummy head recording.

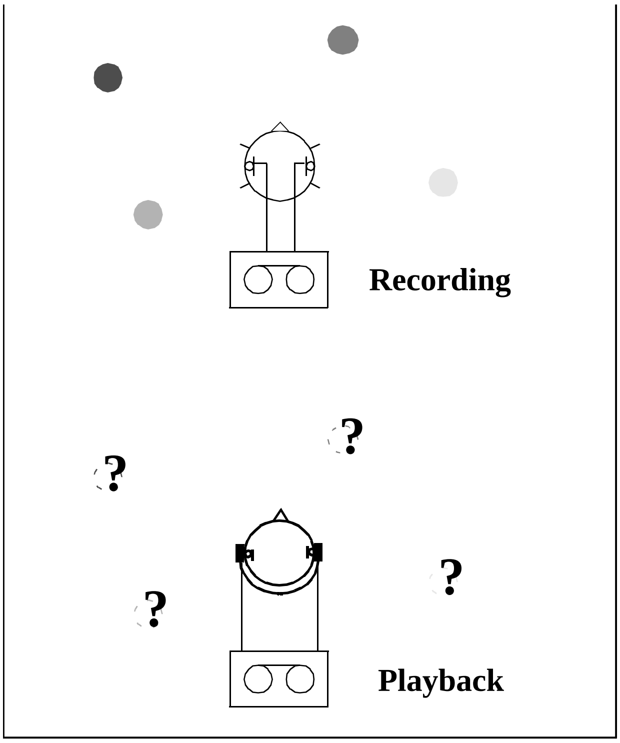

Figure 2. The principle of binaural recording (top) and playback (bottom). In ideal conditions the different auditory events in the recording situation (top, filled circles) are perceived in the playback situation at exactly the same locations (bottom, open circles). Under non-ideal circumstances different aspects might result in localization errors (see text for explanation).

Especially for tasks where very low frequency sounds have to be evaluated, binaural technology may need some extension. Very low frequencies are not only received by the ears, but also by the whole body - we feel the bass in our stomach. This feeling of course is missing in headphone representations. Attempts have been made to give a more realistic feeling by using an additional sub-bass loudspeaker or an active subwoofer.

In summary it can be stated that binaural technology offers the best technical solution to pick up and store sound in a way which is compatible to human hearing, so that this technique really deserves to be called “aurally adequate”.

But, for some applications of sound quality evaluation, it might be necessary to pick up more than just the overall sound of the dummy head. This is especially of advantage if the influence of a single sound source, e.g., an electric motor, in a mixed sound, e.g., the indoor car sound, has to be evaluated. Thus some of the systems offer multichannel recording facilities, so that besides the two channels for the dummy head further signals can be recorded. With regard to this feature the specifications of the systems differ since they have to cope with limitations of their hardware design. In addition to that, some systems offer additional channels for control signals like rpm-information or temperature (requiring a lower sampling rate and bit-resolution).

A completely different approach to acquire acoustical signals are simulation tools. FEM and BEM models can be used

signal acquisition

- **single channel recording**
  + *cheap & easy*
  - *generally not advisable for SQE*
- **binaural technology**
  + *aurally-adequate: dummy head or in-ear microphones*
- **multichannel recording**
  + *combination of binaural recording plus additional channels (acoustic signals, control signals)*
- **simulation**
  FEM/BEM-methods to predict radiated sound
  + *direct link to physical source*
  - *problem: accuracy not yet sufficient*

Figure 3. Advantages and disadvantages of signal acquisition techniques

to predict the sound field which is radiated from a product. This aspect will be discussed in more detail by Keiper [7]. The principal and important advantage of such a simulation is the direct connection between the resulting sound and the physical origin. If it would be possible to calculate the radiated sound with a sufficient accuracy, the product could be evaluated even before a prototype is manufactured. The main advantage would be that the sound could be improved by direct controlled modification of the physical source, namely the product itself - the design of the product could be changed and the effect on the sound quality directly evaluated. This means that at the end of the process of finding the optimal sound also the corresponding product is directly designed - a relation which is not established for signal modification tools which will be discussed in Chapter 5. But, the problem with these simulation methods is indeed the accuracy of the predicted radiated sound - it still does not appear to be sufficient for sound quality evaluation tasks yet, where rather fine details can be quite important. On the other hand, the ongoing improvements of those methods will open new perspectives for the future. Figure 3 summarizes the advantages and disadvantages of the different signal acquisition techniques.

4. Signal analysis methods

Once acoustic signals are stored on a computer, any kind of analysis can be applied to them. This analysis can either be performed online, or, for more complicated tasks, offline in batch processing. The online analysis offers the advantage that it is much easier and faster to optimize sounds - changes can directly be assessed. This is especially useful if the analysis is coupled with signal modification or synthesis methods, so that an optimization can be achieved using direct adaptive methods (see section 5).

In the context of aurally-adequate sound quality evaluation instrumental methods have to be compared to sound evaluation by humans. Since these topics have extensively been discussed in the previous presentations by Blauert and Jekosch, Fastl, and Guski [1,2,3], the background will not be repeated here.

Signal analysis methods offer measures which can be grouped into different categories corresponding to their motivation:

- basic (or standard) signal analysis (level, spectrum, ...);
- auditory models for signal representation (aurally-adequate frequency representation, cochlea models, binaural models, auditory scene analysis, ...);
- indices to predict psychoacoustic quantities (loudness, roughness, ...);
- indices to predict global evaluation measures (Sensory Pleasantness, Annoyance Index, Sound Quality Index, ...).

The first category comprises the traditional way to analyse signals from a pure physical point of view - it is not claimed to have a strong relation to audition. The second category does not directly yield a kind of single-value measure (called index from now on) which represents an evaluation results, but leads to a signal representation which comes closer to what the auditory system does. It is thus a means for further analysis. The latter two categories have the pretension to determine aurally adequate indices - their intention is to predict results of sound evaluation by humans. The categories will be discussed in the following sections.

4.1. Basic Signal analysis

The relation of basic signal analysis methods to audition is rather abstract. Nevertheless, a simple sound pressure level gives a rough impression about the perceived loudness, and a spectral analysis gives - to some extend - basic information about a variety of perceptual attributes (tonality, pitch). Maybe the starting point of aurally-adequate instrumentation was the introduction of the weighted sound pressure levels, where the hearing threshold (A) or isophones (B, C, ...) have been used to change a pure physical measure, the sound pressure level, into a more aurally-adequate measure, the A-(B,C,...)-weighted sound pressure level. But, it has to be considered that those types of weighted levels should not be called aurally-adequate measures - they have to be regarded as a first step into the direction of aurally-adequate instrumentation. The corresponding aurally-adequate measure is indeed loudness, which will be discussed in the next paragraph. Figure 4 summarizes features of the basic signal analysis methods.

4.2. Aurally-adequate signal presentation

The most common way to assess the frequency composition of signals is the Fast-Fourier-Transformation (FFT). This method offers a computationally effective way to transform signals into the frequency domain. If the transformation is continuously applied to segments which are sequentially taken from a time signal, the resulting spectrogram combines the representation of temporal and spectral characteristics.

The major drawback of the FFT is the fixed frequency resolution, which means that the signals are represented by frequency channels of constant absolute bandwidth. This stands in clear contrast to the frequency resolution of the human auditory system: the bandwidth is small at low frequencies and wider at high frequencies. Although third-octave filters represent this behaviour, their frequency resolution is too poor for many sound-quality evaluation tasks.

A principal approach to overcome this problem is the development of auditory models. They can be closely related to signal processing tasks, e.g., the model proposed by Sottek [8], or closely related to physiology. Research has come up with a variety of auditory models:

- models of the periphery: the stages up to the inner ear are simulated, so that the frequency analysis as performed by the auditory system is replicated. This can - to some extend - also be done by FFT-based methods which use for example an FFT with a long time window (equivalent to high frequency resolution) for the low frequency region and an FFT with a short time window for the high frequency region;
- models of binaural hearing: sound localization and binaural selectivity are reproduced, sounds can be extracted from a mixture of signals;
- auditory streaming models: the auditory scene is analysed, and the individual acoustic objects are formed (e.g., the single instruments in an orchestra).

Nevertheless, especially the latter two kinds of models are not yet suitable for sound quality evaluation tasks. But, they offer challenging possibilities for the future. Once those models work reliable, they are able to separate a complex sound into its basic components, which can then be assessed individually. An overview of current models of the human auditory system is presented in Acustica & acta acustica Vol. 82, 1996, Suppl. 1, 85-92.

Basic signal analysis methods

(level, spectrum, spectrogram, ...)

\+ **users are familiar with them / used to interprete them**

– **relation to audition rather abstract**

– **give only rough (and sometimes incorrect) impression about perceptual attributes**

• **attempt to make them more aurally-adequate: frequency-weighting of levels (A, B, C, ... -weighting)**

but: weighted levels are not aurally-adequate!

Figure 4. Features of basic signal analysis methods

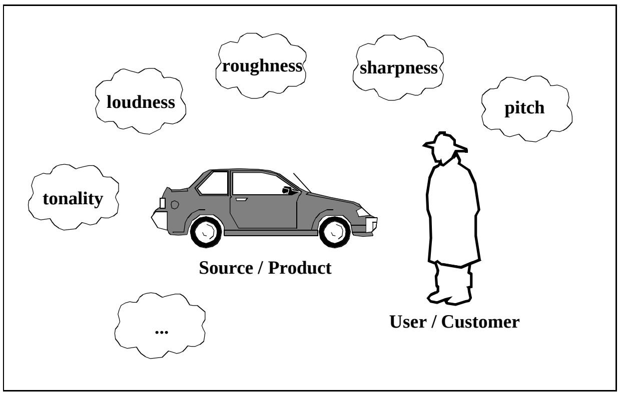

Figure 5. The pool of psychoacoustic quantities

4.3. Psychoacoustic indices

As it has been discussed before and by other authors, auditory events can be broken up into different perceptual components, which are called auditory attributes. The engineering approach to characterize auditory events is to decompose them into a set of - hopefully even orthogonal - auditory attributes which span up the perceptual space. These attributes usually have to be determined and quantified in listening tests.

It is important to note at this point that the link between the auditory attributes and instrumental methods is called psychoacoustics. Following the definition, psychoacoustics is the science which deals with the relationship between parameters of acoustic waves and attributes of auditory events. Thus, as a result of psychoacoustic research, so-called psychoacoustic quantities have been developed. Based on the relation between those quantities and parameters of the acoustic waves methods for the calculation of psychoacoustic indices have been proposed. The psychoacoustic indices hence are instrumental methods to predict psychoacoustic quantities. Figure 5 depicts that the psychoacoustic quantities define a pool of descriptive parameters of the sound.

Today, a variety of psychoacoustic indices can be calculated, and some of them are even international standards: loudness [7, 9, 10, 11] for stationary signals, roughness, sharpness, fluctuation strength, tonality, and pitch. The corresponding psychoacoustic quantities have been discussed in detail in the article of Fastl in the same issue, and a general survey can be found in [12]. It has to be emphasized again at this point that the psychoacoustic indices listed above are instrumental methods to predict psychoacoustic quantities.

An important point has to be considered when those indices should be applied to sound quality evaluation tasks: some of those indices are not general in that sense that they can be applied to any kind of signal. The development of the indices is based on corresponding psychoacoustic investigations, and those investigations often have only been conducted for specific types of signals yet. First, some of the indices have been developed on the basis of stationary signals, e.g., loudness as standardized in DIN 45631. Second, all of the above mentioned indices are only defined yet as monaural indices, which means that they are calculated for each ear independently from the signal in the opposite ear. In contrast to that we know that the auditory system combines signals from the left and the right ear, so that the binaural indices might differ in some cases and to some extend from the monaural ones. But, those indices are still under investigation, and until they will be available the monaural ones can serve as sophisticated tools for sound evaluation (see, e.g., [13, 14]).

Further indices are sometimes applied which are known from speech technology: the Articulation Index (AI) and the Speech Interference Level (SIL). These indices have been developed to give information about the quality of speech, and mainly restricted to intelligibility. Nevertheless, they are sometimes applied to other types of signals, maybe more as a kind of heuristic approach to find a characteristic quantity for a signal.

The psychoacoustic indices have become rather popular in the past years, since they were able to show that instruments can predict perceptual attributes with sufficient accuracy for a wide range of applications. As a consequence, several sound analysis tools are on the market which calculate some or all of the above mentioned psychoacoustic indices. Since all of them are software tools, new indices and improvements of existing indices can be updated easily. The different tools will be discussed in more detail in section 7.

4.4. Combined indices

The psychoacoustic indices can be used to render a global description of a sound in the form of a set of different auditory attributes. Nevertheless, still the final evaluation stage is missing - how should the final evaluation result be determined from a set of these indices? This question might be one of the central questions of sound quality evaluation - since it shows the limitations of pure acoustic approaches. It has been mentioned in the introduction that there exists a variety of different attributes - but humans just select about four of them in the sound evaluation process. This fact would make the task even easier - if their would be a general rule on which attributes are selected! The real problem in this context is that the selection of attributes is influenced by cognitive and emotional aspects. But, if those influencing factors can be controlled, the most important attributes can be determined - but only for this specific situation.

In order to overcome this problem some indices have been proposed which yield a global quality index. But, it becomes obvious from the discussion above that those types of indices can only render reliable results for rather limited and well-defined tasks. Examples of these types of indices are:

- Annoyance Index: this index has been developed by AVL [15, 16]. The application of the annoyance index to engine noise will be presented by Beidl & Stucklschwaiger [17];
- Sensory Pleasantness: Aures [18, 19, 20] proposed this index as a combination of loudness, roughness, sharpness, and tonality. He was able to show correlations of 90 % between the predicted quantity and the psychoacoustically determined quantity. According to the definition this index is a sensory quantity, which means that it purely describes auditory attributes without considering other influencing factors like cognition;

In contrast to those global indices specific sound quality indices for specific applications seem to be more reasonable. If, for example, the influence of a single component, e.g., the gear rattle, on the quality of the indoor sound of a car in specified driving situations should be evaluated, appropriate instrumental methods may be derived from comparison of signal analyses with results of listening tests. The resulting index in that case might consist of a weighted combination of standard signal analysis indices, psychoacoustic indices, or even newly developed specific indices. An example for a combined index offered by the tools is the Composite Rating of Preference which is available as a module for the LMS Sound Quality System.

It can be expected that several other indices have been developed, but are not published and kept confidential. The reason for that is simple: since those indices are really specific, they have been developed by industry in order to have an advantage on the competitive market.

The specific indices discussed above have a consequence on the selection of the appropriate tool for sound quality evaluation: if a user intends to develop his own special indices, tools with an open architecture are of advantage. Open architecture in this context means that own software modules can be combined with the tool. The highest flexibility offer systems where own modules, written in standard programming languages like C, C++, or Fortran, can directly be included into the system. In doing so, the own modules can be integrated into the complete analysis flow at any point. Less flexible systems just offer export possibilities for analysis data, so that standalone modules have to be implemented. On the other hand, “closed systems” can offer an easier to handle user interface.

5. Signal manipulation

The methods described up to now allow for an evaluation of a sound which has been recorded in advance, and thus been emitted by a real physical source. Once an evaluation of this sound has been performed, the following task usually will be an optimization of the sound. An elegant and fast method to find the optimal sound (target sound) is the iterative manipulation and evaluation of the sound until an optimization criterion is fulfilled.

To do so, the signal can be manipulated by means of digital signal processing methods, and the modified sound can be evaluated again by instrumental indices and/or an evaluation by a human listener.

Most of the tools which calculate psychoacoustic indices also offer signal manipulation and signal generation methods. Some of the modifications can be performed in realtime, others have to be calculated offline, depending on the hardware power and the desired amount of modification, e.g., the number of filters to run in parallel. The manipulations offered usually are

- sound editors to modify the time course of signals;
- standard FIR or IIR filters;
- filters with user-defined arbitrary shapes;
- filters controlled by external parameters, e.g., rpm information.

The latter possibility is especially useful for analyses of car sounds, or sounds which show a comparable relation to an excitation source like the firing of cylinders of the engine. If a filter can be adjusted to an engine order, non-stationary signals with changing engine speed can directly be evaluated.

In summary, signal modification methods allow for a fast definition of target sounds. But, once this target sound is found, the product emitting the sound has to be modified in order to meet this target. Thus, in the process of sound modification, the link to the physical source has to be kept in mind by the user of the system - it has to be possible to modify the product in such a way that the target sound is emitted! In addition, the interaction aspect between the sound source and the user can not be adequately considered with those systems - the evaluation is based on fixed recordings which a listener (or the instrument) judges on without interacting with the product. Approaches to overcome these problems will be discussed in the following paragraph. Figure 6 summarizes the signal manipulation flow.

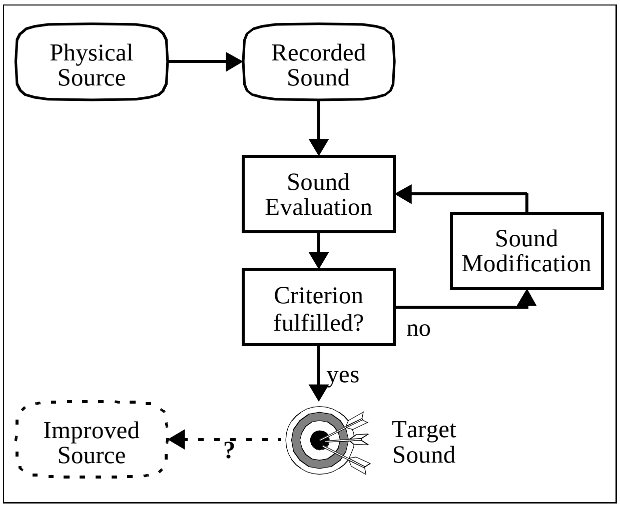

Figure 6. Signal manipulation process of recorded signals. The target sound can conveniently be defined, but the direct relation to the physical source is lost (see text).

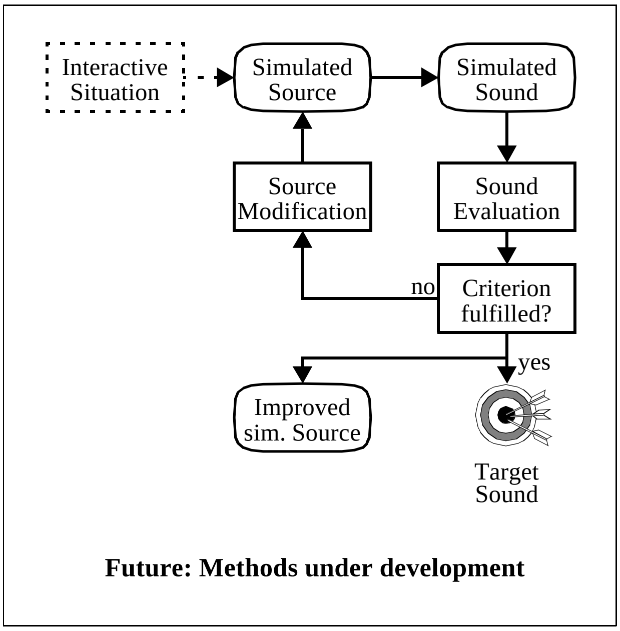

Figure 7. Signal manipulation process using a complete simulation of the source. Besides the definition of the target sound, the link to the physical source leads to a direct improvement of the product. The grey blocks represent methods which are still under development and not yet accurate enough to be used for sound design tasks.

6. Simulation and Interactivity

The evaluation instruments discussed up to now can be regarded as systems which reproduce a laboratory investigation - sounds are recorded, and afterwards they are evaluated, either by calculating instrumental indices or by human evaluation. This differs to some extend from the way how we judge on the sound quality of a product. Usually we will make up our judgement while we use the product - we will hear how the product sound reacts to our action.

The ideal solution for this problem would be the complete acoustical simulation in realtime, so that on one hand signal modifications can be performed, and on the other hand the user can control the status of the product. This scheme, which is depicted in Figure 7, will surely be a future perspective of sound quality evaluation, but today's available simulation tools are not accurate enough or computationally too expensive to run in realtime.

But, as mentioned in the previous chapter, some sound quality tools allow for a realtime modification of signals controlled by a third parameter, e.g., the engine speed. Thus an interactive investigation is possible with today's available methods using a hybrid approach: the original signal in a driving car can be recorded, modified in realtime, and directly played back to a passenger via headphones. This approach will be presented by Bisping [21], so that it will not be discussed here.

Philosophies of tools

- **specific hardware**
  - *DSP boards, transputers*
- **standard hardware**
  - *PC or UNIX workstations*

- **stand-alone systems (closed)**
  - *ready-to-use, no integration of own modules, but data in- and export*
- **semi-open systems**
  - *include own precedures in meta-language*
- **complete open systems**
  - *include own modules in standard programming language (Fortran, C, ...)*

Figure 8. Hard- and software philosophies of tools for sound-quality evaluation.

Selection of appropriate tools

- **specific feature requirements**
  - *realtime signal modification requirements*
  - *user interface design*
- **hardware requirements**
  - *specific hardware*
  - *multi-purpose hardware: PC or UNIX based*
- **system openness**
  - *pure enduser: closed ready-to-use systems*
  - *enduser which might develop own procedures: semi-open or open system*
  - *developer of evaluation tools: open systems*

Figure 9. Aspects for the selection of the appropriate tool for sound-quality evaluation.

7. Tools for sound quality evaluation

As it has been stated before, the strong market demand for instruments to evaluate the quality of sounds has led to an increasing number of tools for sound quality evaluation and sound design. Especially the standardization of psychoacoustic indices like loudness and low-cost digital signal processing hardware made it rather easy to include psychoacoustic indices into sound analysis methods.

A comparison of tools which are on the market today shows that the sum of features of the systems appear to be rather similar: all of them include standard signal analysis methods, a set of psychoacoustic indices, and signal manipulation and generation tools. The main differences between the systems have to be searched in their basic hard- and software philosophies: they range from completely closed, stand-alone systems on special hardware to completely open systems on standard hardware. This has an impact on the user-interface - closed systems can be designed in that way that their operation is easier - whereas a completely open system requires more knowledge about the system, especially if the user intends to implement and integrate own modules - but the user has the opportunity to extend the system if he develops his own indices. Figure 8 gives an overview on the philosophies of the tools.

Since the signal evaluation methods are implemented in software, they are under continuous development by manufacturers, so that some features of individual systems which are on the market might change quickly. In comparing the systems special attention has to be given to specific features. One example is the feature “Multi-channel-input”, where the maximal available number of channels and the maximal available sum sampling rate (the sum of the sampling rates of each used channel) is limited by the hardware. Some suppliers also offer hardware extension features in order to allow for more channels.

Further differences have to be noted with respect to psychoacoustic indices. Besides the loudness of stationary signals some suppliers have implemented (or announced the implementation) of time-varying loudness, and some illustrate also specific loudness quantities, the loudness contribution of each frequency band. A more critical aspect is the reliability of the rendered indices, especially for cases where the quantities are not (yet) standardized. The only way to overcome this problem is indeed a further standardization - although this might easily conflict with the fact that many aspects are still under ongoing research, so that a too early standardization might on one hand hinder the ongoing work and on the other hand might show up to be incorrect at a later point. Another possibility would be the creation of a kind of “benchmark signal database” which could be used to directly compare the output of the systems.

With regard to signal modification abilities systems differ due to different hardware power. Usually the number of parallel filters or the complexity of the filters for realtime application is limited. Signal editors also show some different features.

In conclusion of the above, the appropriate tool has to be selected according to the specific requirements, the working environment, and the personal preferences, as shown in Figure 9.

Features and philosophies of future instrumentation tools are summarized in Figure 10. As stated before, psychoacoustic indices are under continuous development. The existing indices are improved, new indices are developed, and finally binaural indices will have to be defined. In addition to that, more general models of sound perception can be expected which comprise effects of sound localization and the influence of cognition. Improved simulation tools will hopefully allow for a sufficient accurate modeling of the physical sound

Future Instrumentation

- **psychoacoustic indices**
  - *improvement of existing indices*
  - *development of new indices*
  - *development of binaural indices*
- **perception models**
  - *localization, selection & evaluation of sounds considering cognition*
- **simulation tools**
  - *sound radiation in realtime / sufficient accuracy*
  - *environmental simulation in realtime / sufficient accuracy*
  - *development of interactive tools*
- **product / task specific solutions**
  - *development of product / task specific expert systems to select the relevant quantities*

BUT: instrumental tools haveto be used by experts

Figure 10. Future instrumentation for sound-quality evaluation.

radiation, which is the prerequisite for a complete integration of interactivity. Due to the complexity of the underlying problem, product and task-specific approaches might offer promising solutions for sound-quality evaluation purposes.

8. Conclusions

As a result of psychoacoustic research, a set of psychoacoustic indices has been developed which allow for an instrumental prediction of attributes of sound perception. These indices offer - in combination with acoustic workstations for aurally-adequate sound recording, standard signal analysis and signal modification - a powerful tool for the assessment, evaluation, and improvement of sound.

Nevertheless, instruments are far from simulating human sound perception and evaluation in all its facets. They have to be more regarded as tools to evaluate sets of specific features of sounds, and less to give a global and final evaluation result. Furthermore, the expertise of the user is a crucial requirement for the success of the evaluation process - he has to be aware of the meaning and the limitations of the instrumental indices rendered by the tools.

It is not the intention of this article to recommend one of the tools which are available on the market. The comparison shows that the systems have different basic philosophies with regard to their hardware and software basis, so that the appropriate system for each user has to be selected according to his specific requirements, his working environment, and personal preferences.

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