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PRODUCT-SOUND QUALITY: A NEW ASPECT OF MACHINERY NOISE

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Quality is an issue of current attention with regard to product-sound design and assessment as it has now been widely recognised that the quality of the sound that a product makes is a significant component of the consumers' overall judgement on the product. This trivial fact has long been neglected by engineers and – much to their concern – they are now more and more pushed to take account of it in the product-development process. It is the aim of this article to provide the basis for a more differentiated view on product-sound quality than is currently common in the field. Special focus will be put on the process of perception and judgement in the context of quality assessment. It is hoped that engineers are encouraged to take on product-sound design and assessment as a generic engineering task.

1. Acoustic events and the concept of noise

"Noise" is usually defined as an unwanted acoustic event, in other words, an acoustical event that one would prefer to switch off or at least to modify – if this were possible. This simplified definition implies a basic feature of noise: To classify an acoustic event as noise, somebody must actually make the judgement "unwanted".

An acoustical event is mechanical oscillations and waves in elastic media. Consequently, it is a purely physical phenomenon. Since an acoustical event represents mechanical energy, it can apply forces and, accordingly, can have destructive effects on structures. Such effects are, for example, causing cracks in mechanical structures, degrading the function of instruments and/or causing damage to the hair cells of inner ears – such reducing the sensibility of the auditory system.

With respect to the mechanical effects of forces applied by an acoustic event, the decision of whether an acoustic event is unwanted or not, can be taken on physical or biophysical evidence. Threshold values can be found on the grounds of results of physical or biophysical measurement. Nevertheless, the judgement of experts such as mechanical engineers, acousticians, medical doctors, economists, lawyers and, ultimately, politicians is needed to establish thresholds as we find them in laws and other official regulations.

An obvious cure against mechanical, destructive effects of acoustic events is the following. Reduce the energy of the acoustical event, resp. the acoustic level. "Lower is better" – applied to the acoustic level – is indeed the most often applied recipe in noise engineering. It has the advantage of offering a straight forward, one-dimensional instruction for action, very much like the fundamental capitalistic demand to maximise profit. Yet, already in the domain of mechanical effects of acoustic events, which we are talking about at this time, one can find examples which show that the simple "linear" action of reducing the level is not always optimal. For example, when a high-Q resonance in a mechanical structure is excited by a narrow-band acoustic event, it is often much more effective to modify the tuning than to reduce the acoustic event level.

From the point of view of the effect of noise on humans it seems to be established that a permanent biophysical damage to the human ear will most likely be avoided when the level of a stationary acoustic event which the ear is exposed to for an extended period, stays below about 85 dB (A). It is, however, not the case that all acoustic problems with respect to humans are solved, once the level is sufficiently low such as to no longer be biophysically harmful to the inner ear. For this reason we shall now turn to the discussion of noise situations with levels well below 85 dB (A), in order to evaluate the question of what factors then govern the decision of whether an acoustic event is unwanted or not. We shall see that in these cases the essence of the decision is psychoacoustical and psychological rather than physical or biophysical.

2. Auditory events

Under normal circumstances a person being exposed to an audible acoustic event will hear "something". This something is, to be sure, not the (physical) acoustic event, but and outcome of auditory perception which we call auditory object or auditory event. Auditory objects, like any other objects (e.g. visual or tactile ones) have particular spatial and temporal attributes (they exist at a specific location at a specific time) as well as particular qualitative attrtibutes (in the case of auditory objects, for example, loudness, pitch and timbre). The decision of whether an acoustic event is noise is made by the listeners on their auditory perception, i.e. by judging on the characteristics of auditory objects.

This situation raises the question of whether listeners can dislike auditory events per se, i.e. by disliking specific auditory attributes or groups of attributes of the auditory events. There is no definite answer available from psychological theory, but these authors tend to say yes. The following hint may be used to support this view. Loud auditory events – like bright visual events – can be annoying in the sense of being straining to listen (look) to. Further, there seems to be a very basic kind of aesthetic quality of auditory events which makes them acoustic events pleasant to listen to, sometimes called sensory consonance.

Loudness and sensory consonance are quite basic auditory features, which require little or no abstraction. Yet, there are other, often much more important features of auditory events which prompt the listeners' judgements in terms of wanted or unwanted. As an example, consider the buzz of a mosquito circling your head when trying to find rest. How can such an auditory and, consequently, acoustic event be assessed?

3. The information aspect

Consider the physiological role of the auditory system: It is purpose of this system to gather up and process information from and about the environment, including tasks such as to identify acoustic-event sources with respect to their nature and their position and state of movement in space. Further in many species as in humans, interindividual (vocal) communication is performed through the auditory system.

With regard to auditory information gathering and processing, there are the following reasons to classify an acoustic event as noise, i.e. as being undesired: (a) An acoustic event carries information which is unwanted, undesired. (b) An acoustic event hinders the perception of desired information and is thus rated as being undesired.

Certain cars are liked by enthusiasts because of their characteristic engine acoustic events. The engine acoustic event "signals" information about the type of car. From a different point of view it is, nevertheless, noise. In more general terms, each acoustic event carries information about the acoustic-event source and its present state. The operator of a machine wants to hear the characteristics acoustic event of the machine in order to be sure about its proper functioning – and also to avoid accidents. Typical acoustic events may indicate, e.g., whether a device is switched on or off.

If an acoustic-event component has a double role of being signal and noise at the same time, depending on the point of view, a pure level reduction will have the following effect: The annoying effect of the acoustic event will be reduced and so the acoustic event will become less noisy. At the same time the function of the acoustic event as signal will be impaired and an acoustic-event situation may result which is rated to be even more undesired. It is obvious that noise problems of this kind must be very carefully evaluated. Instead of aiming at just reducing the noise level, although this is often a good thing to start with, the engineer must consider a (re)design of the complete acoustic situation – and also be aware of the particular non-acoustic environment.

When an acoustic event carries information this means that the acoustic event stands for something else, i.e. that it acts as a sign, a signal. This is, in other words, that a "meaning" is assigned to it. Actually, it is quite common that meanings are assigned to acoustic events. The most evident example is spoken language, which is actually a highly standardised code. To decipher the meaning of speech-acoustic events, the listener must know the code, i.e. the language.

In cases of acoustic events other than speech the meanings are less standardised and subject to individual interpretation. The way in which a listener interprets the meaning of response carried by an acoustic event will influence his judgement in terms of wanted – vs. unwantedness to a considerable degree. Yet, there may be inherent meaning in certain acoustic events which are understood by many people in basically the same way – obviously on a low level of abstraction. For example, particular acoustic events have been found which, when being used as warning signals, indicate such things as "Fire! Leave the house!" in contrast to "Gas alarm! Stay inside and shut the windows!"

Expectations are an important factor in this context. A coffee machine sounding like an electric razor would be rated bad although the sound might be perfectly o.k. for a razor. Obviously we expect the sound of a coffee machine to signal something very specific which is not given by the sound of a razor.

4. Cognitive factors

The interpretation of meanings assigned to auditory events requires involvement of higher processes of the central nervous system, known as cognition. A simple model of the process of judgement could be as follows. Listeners set up hypotheses with regard to the meanings of their perceived auditory events based, among other things, on their current cognitive situation. Then they test these hypotheses on the basis of all relevant information currently available to them. Besides information from the auditory modality, prior knowledge and information from other senses, e.g., vision, may be used, current actions and emotions may to be considered as well.

In the context of research on the effect of traffic noise on humans, a number of cognitive factors have been identified which play a role in the formation of hypotheses in listening and, consequently, affect both auditory perception and judgement. Some more important ones are listed in the following as examples.

Factors related to the sound sources

When judging on auditory events, listeners reflect on their specific conceptual image of the acoustic sources. For example, the auditory events stemming from acoustic sources considered dangerous tend to be rated significantly louder and noisier than those from sources considered harmless. Experimentally this has been shown by presenting pictures of different sources to subjects together with the same acoustic signal. The conceptual image of an acoustic source is of particular influence on the judgement of the auditory event attached to it, e.g., when the source behind it is a human being considered to have bad intentions, or a process considered dangerous or unhealthy. On the contrary, when acoustic sources are considered positive, such as strong, healthy, lively, beautiful, the auditory events attached to it tend to be rated lower and less disturbing.

Factors related to the situation

Depending on the situative context, auditory events are rated differently. For example, in a situation perceived as comfortable, auditory events are judged upon in a different way than in an uncomfortable situation. Aesthetics must be taken in consideration also. Of special importance is the particular state of activity (action) of the listeners, e.g., working, relaxing, sleeping. It may be required for good quality that the acoustic events change in the context of a listeners activity, e.g., to signal that an operator's commands are executed. The specific role of oral/auditory communication has to be taken into account in particular. Acoustic events which interfere here, are especially disturbing. Specific situations and activities require specific acoustical conditions.

Factor related to individuals

Personal factors, i.e. such which are related to individual listeners, are of special importance. They usually represent the dominant reason for interindividual variance and, consequently, increase the degree of subjectivity of the judgements. The understanding of personal factors is, among other things, relevant for the formation of panels of listeners which can be considered representative for the target population for certain products. Expectation is an important factor here, others are motivation, attitude, taste, economical situation, experience.

5. Auditory perception and measurement

Judgements by listeners are commonly called "subjective". Such a usage of the term "subjective" results from a lack of differentiation, however. Adequate psychometric methods may well render results which are largely independent of individual listeners and thus "objective". Hence, in psychoacoustics the term "objectivity" is preferably understood as follows. Objectivity is given when the statistical distributions of judgements are the same for each of the subjects and, insofar, independent of any individual subject. Complete objectivity is not to be expected from listening tests. In praxi, results are achieved which are more or less subjective or objective. The degree of subjectivity increases the more individual characteristics of subjects influence their individual perception and judgement.

Instrumental physics uses a very restricted definition of measurement as follows: Measurement is the quantitative assessment of the ratio of a physical quantity with respect to a reference quantity of identical dimension. A more general definition of measurement comprises any assignment of numbers to objects in such a way that relations between the numbers reflect relations between the objects. Psychoacoustic judgements can be subsumed under such a general concept of measurement, provided that the judgements map relations between attributes of percepts in a quantitative way. In experimental procedures which render this kind of results, the subjects act as a measurement device to measure their own percepts.

It is clear at this point that measurement is not restricted to instrumental physical techniques, but that it is also possible with psychological and psychophysical procedures, i.e. with the involvement of subjects. Yet, the results of tests with subjects tend to show higher variance than usually encountered with instrumental measurements.

Engineers are educated in a way which has its roots in more-than-a-hundered-year-old conceptional approaches of applied physics. Consequently, they often have an over-simplified idea of objectivity. They think that any experiment within their science is designed in such a way that the observers do not take part in the experiment in principle and that, for this reason, the process and the results of the experiment are completely independent from observers.

Engineers, in this context, are thus used to assume that only such data have any relevance in reality which have been acquired independently of any observer. A further specific feature of the conservative engineering approach is that more complex phenomena are usually dealt with in an analytic way, i.e. with the attempt of decomposing them into, preferably orthogonal, components. The idea behind this is the assumption that the original phenomena can completely be resynthesised from these components. Such a method of analysis and resynthesis has indeed been successful in many cases, see for example the Fourier analysis/synthesis in signal processing. It is, however, inadequate for problems where observers are intrinsic to the experimental procedure, as it obviously the case in psychoacoustic assessment.

There is no way out than recognising the observer as an integral part of the experiment and to accept that "absolute" objectivity cannot be achieved. Further, it has to be accounted for that observers cannot only influence the progress of the experiment, but also go through changes themselves in the course of the experiment. Observers may, for example, enhance their ability to detect certain perceptual attributes, or they may change their judgement criteria.

When dealing with problems of perception and judgement the complete system comprising the perceived object as well as the perceiving and judging observer must be dealt with an integrated way. Any concern that this would require to leave the area of rational scientific argumentation is not justified, simply because the brain as the organ of perception and judgement is a purely biological organ after all.

6. Product-sound quality: A definition

So far, in this article, we have dealt with the fact that an acoustic event can be assigned the attribute "noise", based on human judgements of negative physical effects of the acoustical events or judgements on the undesirability of the auditory events attached to the acoustic events under consideration. By calling an acoustic event a "noise", we actually put it in a certain "quality" category. In fact, the concept of "quality" has recently gained much broader relevance in acoustics. In the following, we introduce a modern definition of sound quality as appropriate in the context of industrial products, and discuss some major implications for sound-quality evaluation following from this definition.

In the following the familiar term "sound", which is often used equivocally for both the acoustic events and the auditory events attached to it, will be used for the auditory events – and only for those. In pursuit of a concept of the 2nd author product-sound quality can be defined as follows, whereby the term "product" may be associated with specific samples of a product as well as with a class of products:

"Product-sound quality is a descriptor of the adequacy of the sound attached to a product. It results from judgements upon the totality of auditory characteristics of the said sound – the judgements being performed with reference to the set of those desired features of the product which are apparent to the users in their actual cognitive, actional and emotional situation."

The prerequisite for sound quality to happen is obviously the existence of a product which emits acoustic waves, such as to initiate a percept of sound to be judged upon in terms of quality. Upon hearing something which obviously stems from the product considered, the listeners take on the task of judging upon their auditory events. They judge by using a frame of reference which, in the definition above, is called "set of desired features of the product". It goes without saying that the listeners will only judge with reference to desired features which are apparent, and that this process does evidently depend on the cognitive, actional and emotional situation given.

The involvement of cognition is easily envisaged. The listeners use to have prior knowledge of the individual product of sample or class of products under consideration. It is assumed that they judge by comparing the attributes of their auditory events with the set of desired features of the product which they have in mind. As a result of this process they finally come up with a judgement, which then, in turn, is assigned to the product as being its sound quality. Sound quality, hence, is not an inherent property of the product, but rather something which develops when listeners are auditorily exposed to the product and judge on it with respect to their desires and/or expectations in a given situational context.

Following the definition of sound quality presented above, the assignment of sound-quality to auditory events requires judgements – the judgement being performed with reference to a concept of desired features of the product. In other words, the idea is that the listeners compare their auditory events with an internal frame of reference of theirs, and thereupon issue their quality statements – be it global statements like values on a scale bad-to-good or more differentiated statement following analyses with respect to distinct quality features.

If the frame of reference would just require pleasantness (sensory consonance) of a sound as the desired quality feature, basic psychoacoustic quantities might suffice to establish a quality statement. Yet, sound-quality engineers dealing with the sound quality of industrial products will rarely get off that easily. The user and/or prospective user of a product comes up with concepts of desired features which are quite complex. Among other things, the scope of desired features is not restricted to features of the sound only, but to other features of the product as well. From an industrial product the user requires flawless and efficient functioning in the first place, but many additional items like the aesthetic appearance and the product image in a social context play an important role as well. Pleasantness of the product sound is, in fact, not very high-ranking in the hierarchy of desired features.

We have already mentioned that sounds are carriers of information, e.g., they are signals and signs of activities in the environment. In the light of this statement it becomes clear that the sound of a product has a particularly important function, that is to say, it informs the user about the presence of a product and about its state of operation in space and time. A product may, for example, indicate to the user, among other things: I am the electric razor in your hand, and I am switched on. My blades are cutting the hairs of your chin properly, but I may need a battery recharge soon.

To be able to decipher these messages of the razor, the users have to know the "language" of electric razors. They must have an idea of how a good razor sounds when functioning properly, and be able to discriminate fine shades of changes in the sound when the battery is low. They should possibly also be capable of recognising the brand of a razor by its sound. The important point here is that the customers are not only interested in the product sound per se, but that the product sound is a carrier of information for them. They certainly would prefer a pleasant sound to an unpleasant one, but, even more so, they want the "sound of quality".

It is at this point that it becomes evident why the frame of reference which customers are referring to when judging upon the quality of a sound, comprises desired auditory features as well as many kinds of desired non-auditory ones. The sound can meet the demands for auditory quality features directly. Yet, as far as non-auditory quality features of the product are concerned, the product sound can, at best, provide an indication as to which amount these may be met. To be sure, good product-sound engineers are intuitively aware of a lot of general features which high-quality product sounds should have.

7. Approaching sound-quality assessment systematically

From the point of view of product-sound engineering it is of predominant importance to analyse the process of sound-quality assignment systematically. Questions to ask are as follows: What are the constituents at each step of the development of the sound-quality assigned to a product, and how can these be evaluated and engineered in order to arrive at a predetermined product-sound quality.

Some helpful facts to be mentioned in this context are the following: There are methods available to evaluate the relationships between parameters of acoustic events and attributes of auditory events, as already mentioned above, the so-called psychometric methods. It is reasonable to make the following comment at this point: Once the relationships between acoustics parameters and auditory attributes have been established in a reliable, valid and representative way, computer algorithms can be conceived and implemented which render estimators for psychoacoustics quantities by purely instrumental methods.

Yet, it has to be kept in mind that common "peripheral" psychoacoustics, although providing basic knowledge on auditory perception, is not at all sufficient to cover the complex tasks of product-sound quality evaluation and assessment. Three important facts have to be kept in mind additionally to arrive at a more reasonable model for sound-quality evaluation: (a) The acoustic waves have a distinct source, namely, the product under consideration. (b) The process of psychoacoustic perception is augmented by a process of judgement. (c) Both perception and judgement are modified by factors originating from cognition, but also from actions, emotions, and input from non-auditory senses.

Item (a) makes clear that the origin of the acoustic event is the ultimate object of concern here, that is to say, the sound emitting product. Item (b) is introduced to denote that common psychometric measurement does not suffice to assess product-sound quality. The concept of judgement may include processes akin to psychoacoustic measurement, yet, goes far beyond it. It comprises sophisticated global as well as analytic evaluation and assessment, including complex balancing and weighing with regard to issues such as information from non-auditory senses, prior knowledge and association to actions and emotions. It is thus appropriate to regard the process of judgement as a matter of psychology rather than of just psychoacoustics. Item (c) complements the process of judgement by explicitly introducing input from non-auditory modalities, cognition, action and emotion as response-moderating factors. Note that response-moderating factors do not only influence the judgement process, but the process of auditory perception as well. Among other things, this is to make clear that already the output of auditory perception is not at all predetermined solely by the acoustic input to the auditory system, but results from a complex interaction of auditory input, non-auditory input, expectation and mood.

8. Conclusions

Product-sound engineering is certainly not an easy task, and even worse, there is no shortcut to it. Among other things it requires sufficient knowledge and experience at least in the following areas: (1) acoustics, especially related to mechanical engineering, (2) psychoacoustics, i.e. basic relationships of the acoustic input and the auditory output of perception; (3) psychologic effects and rules which govern the judgement processes through which quality statements are formed.

Further, to be able to actually engineer product sounds, product-sound engineers need potent tools, that is tools which enable them to specify design goals and, consequently, shape the product sounds in accordance to these design goals. Obviously, economical constraints have to be met during this process, as is typical for any engineering task.

Whithout doubt, the evaluation activities in the course of product-engineering start at the acoustic end of the quality cycle. It has first to be established what the contributions of the different mechanical parts of the product to its overall acoustic emission. Since the contribution add up linearly in most cases (at least with sufficient approximation), analytic methods of physical acoustics and the usual equipment for measurement of acoustic waves and vibrations can be applied to determine the individual contributions in terms of parameters of sound waves. In such a way, the acoustic input to auditory perception can be evaluated and specified.

Following purely-acoustic evaluation, the next step in the sound-quality cycle asks for an evaluation of the auditory events, i.e. of the "product sound" per se. To this end, product-sound engineers have to perform psychoacoustic experiments themselves, or to refer to the results of psychoacoustic research related to their specific engineering problems – if available. It is of paramount importance at this point to keep in mind that in most psychoacoustic research "unbiased" psychoacoustic measurement is assumed. Consequently, the results can be applied to practical problems only with great care. For some psychoacoustic quantities, for example, loudness and sharpness, modern equipment is available to mimic the process of psychoacoustic measurement electronically. As an output, these instruments render estimates of "unbiased" psychoacoustic quantities – not the psychoacoustic quantities themselves. It is important to be aware of this distinction, especially when the equipment has been standardised. Auditory perception is an individual process influenced by cognition, action and emotion, and is thus hard to be standardised in principle.

Any endeavour to evaluate product sounds by psychoacoustics only will fail in the end. To really understand and control the process of product-sound assessment specific psychologic knowledge and profound experience in the application of research methods as used in psychology are needed. It is at this point were deficiencies in the education of engineers dealing with product-sound design often become apparent. Further, quite frequently a certain shyness of engineers can be observed when it comes to psychological problems.

With regard to the evaluation of the psychology of auditory perception and judgement, the following argument is noteworthy: In the course of the perception and judgement processes a considerable reduction of information takes place. The high number of parameters necessary to represent the acoustical events at the ears of listeners is reduced to a handful of features (usually less than four) which the listeners actually refer to when coming up with a sound-quality statement. Special segmentation processes and "Gestalt" phenomena in perception as well as controllable and uncontrollable selection processes in judgement are to be evaluated and understood as well as the nature and development of the frames of reference which the listeners actually use when judging upon product sounds. As these psychological processes show profound interindividual variance, one of the important tasks of product-sound engineering is to select representative listeners for evaluation procedures – a complex task in itself. Methods for proper selection of subjects are part of the work bench of product-sound engineers. Representative listeners are not necessarily expert listeners!

Once a quality statement on a product sound is available, it will often be a challenge to improve the product sound quality – preferably but not necessarily in turn with an improvement of the product quality in toto. Improving the sound-quality means modifying those parts of the product which produce the sound. As information reduction has taken place in the processes of auditory perception and judgement, and as these processes are non-linear, time-variant and loaded with a huge amount of memory, it is not a trivial task at all to trace the quality cycle backwards. In other words, it is hard to solve this inverse problem, namely, to evaluate which attributes of the auditory events, or – going back even further along the quality cycle – which parts of the product play a role in the formation of its sound quality, and to which quality features are they finally related.

9. References

This article is based on ideas which the authors have presented at an EAA TUTORIUM which the first author had organized in Antwerp at the occasion of the FORUM-ACUSTICUM-1996 convention – and on earlier publications. The journal of the European Acoustics Association, ACUSTICA united with ACTA ACUSTICA has recently published a special issue on Product-Sound Quality (**83**, 5, September/October 1997). This issue comprises the papers presented at the EAA TUTORIUM mentioned above and contains a variety of references to the relevant literature.