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EXPLOITATION OF PSYCHOACOUSTIC VALUES OF STATIONARY SIGNALS FROM GEAR–BOXES

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In this paper, a psychoacoustical analysis of car gear-box noise as well as noise generated by shaft-wheel pairs of gear-boxes is presented. An investigation of the possibility of psychoacoustical analysis application as a non-destructive method of diagnostics of car gear-boxes and shaft-wheel pairs of gear boxes was a motivation for this work. The basic psychoacoustic quantities corresponding to the tested gear-boxes and shaft-wheel pairs were evaluated using Toolbox Psychoacoustic. The results obtained by psychoacoustical analysis have been in correlation with the results obtained by subjective evaluation carried out by "factory sound specialists". This fact indicates that the psychoacoustical analysis could be in many cases a reasonable tool in the field of non-destructive methods of diagnostics of gear-boxes as well as their shaft-wheel pairs.

K e y w o r d s: psychoacoustics, psychoacoustical quantities, diagnostics, quality control

1 INTRODUCTION

Machine condition monitoring based on their noise analysis belongs to the most sophisticated methods of quality control or quality assurance in accordance with the standards of EN 29000 series. Quality control of machinery production represents a fundamental problem, especially in the case of large serial production. Conventional spectral analysis, order analysis, cepstral analysis, higher-order spectra analysis, order tracking analysis averaged in frequency and in time domains [1–4], A-sound pressure level and C-sound pressure level of machine noise belong to very important methods of machinery analysis.

In many cases, a subjective evaluation of mechanical systems carried out by "factory sound specialists" is applied for the purpose of quality control and diagnostics, too. Here, the final decision taken by "a sound specialist-operator" is based on her/his subjective hearing sensations elicited by noise or sound generated by the tested machine under defined conditions. For the purpose of automatic and intelligent quality control and diagnostics, subjective hearing sensations can be modeled using a psychoacoustic approach.

Psychoacoustics represents a basic science which studies the correlations between physically well defined stimuli and the hearing sensations elicited by these stimuli [5]. The basic psychoacoustic quantities (BPQs) are represented by auditory sensations like loudness, roughness, sharpness, fluctuation strength, tonality, critical band rate moments, sensory pleasing sound, unbiased annoyance, *etc* [6–11]. Psychoacoustics provides the background for a lot of practical applications in noise evaluation and control, environmental protection, fault-finding in mechanical equipment and machines, early diagnosis of engine damage, musical acoustics, hearing aids, broadcasting and communication systems, speech recognition, room acoustics, *etc*.

The description of the BPQs, algorithms of their evaluation and availability of a proper measuring instrument are the most important assumptions for effective and successful practical applications of psychoacoustic methods especially in the field of industry. A really very good and comprehensive description of the BPQs including an introduction to psychoacoustics can be found in [6]. The most frequently used algorithms of the BPQ evaluation are given in [7, 8].

In this paper, we will deal with psychoacoustical analysis of sounds generated by car gear-boxes as well as sounds generated by corresponding shaft-wheel pairs of gear-boxes. An investigation of possibility of psychoacoustical analysis application as a non-destructive method of diagnostics of car gear-boxes and shaft-wheel pairs of gear-boxes was a motivation for this work. The BPQs corresponding to the tested gear-boxes and shaft-wheel pairs were evaluated using Toolbox Psychoacoustic — a MATLAB software developed at the Technical University of Košice in co-operation with the Technical Testing Institute of Piešťany [12]. The results obtained by psychoacoustical analysis have been in correlation with the results obtained by subjective evaluation carried out by "factory sound specialists". This fact indicates that the psychoacoustical analysis could be in many cases a reasonable tool in the field of non-destructive methods of diagnostics of gear-boxes as well as their shaft-wheel pairs.

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In order to follow the above declared aims of our contribution, this paper will have the following structure. First, the Toolbox Psychoacoustic applied for BPQs evaluation will be described in Section 2. Here, the structure and properties of the toolbox, methods used for BPQs evaluation, as well as conditions for toolbox applications will be described. Second, the psychoacoustical analysis of sounds generated by car gear-boxes as well as sounds generated by corresponding shaft-wheel pairs of gear-boxes will be done in Section 3. In Section 4, conclusions will be presented.

2 TOOLBOX PSYCHOACOUSTICS

MATLAB is a technical computing environment for high-performance numerical computation and visualisation which belongs to standard software equipment of a signal processing laboratory [13]. This program has been found in hundreds of applications in the field of education, science, technology, industry, *etc* MATLAB features family-specific solutions that are called toolboxes. They are comprehensive collections of MATLAB functions (m-files) that extend the MATLAB environment in order to solve particular classes of problems.

In the field of industrial applications of the psychoacoustics, this class of problem is represented especially by the BPQ evaluation. With regard to MATLAB properties and taking into account our positive experience with this software, we decided to use MATLAB toolbox approach as the software basis for BPQ evaluation. Toolbox Psychoacoustics developed at the TUK in co-operation with the TTIP has been the result of our effort [12].

At the present time, Toolbox Psychoacoustics contains all of the m-files necessary for evaluation of the BPQs from the time waveform of the sound pressure. All of the supported m-files (*eg* functions for design of octave and one-third-octave digital filters, result visualisation, *etc*) are also included into the toolbox. The Toolbox Psychoacoustics consisting of the above 120 MATLAB m-files can be used for the evaluation of the following acoustical and psychoacoustical quantities:

- RMS values of the sound pressure level in the octave or one-third octave frequency band
- RMS values of the A- and C-weighted sound pressure level
- loudness, partial loudnesses and loudness level by Zwicker [6, 9, 10]
- loudness, loudness indices and loudness level by Stevens [11]
- sharpness and relative sharpnesses [6–8]
- critical band rate moments [7]
- roughness and partial roughnesses [7, 8]
- tonality and tonal components [7, 8]
- sensory pleasing sound [7].

The above given BPQs are evaluated based on the assumption of stationarity of the sound pressure. The evaluated quantities can be presented in the form of single data (*eg* loudness), vectors (*eg* loudness indices), and graphs. The graphs contain all of the basic information necessary for building printed documentation on sound signals to be analysed.

BPQ evaluation methods implemented in toolbox are based on digital signal processing application. With regard to that fact, in any Toolbox Psychoacoustics application three facts should be taken into account. They are the measurement system calibration, sampling frequency selection and assumption of stationarity of the signals to be processed. These facts are discussed below.

The sound signal to be processed for the purpose of the BPQ evaluation is picked by a measuring microphone. This signal is amplified and then filtered by an antialiasing low-pass analogue filter. Its cut-off frequency should be chosen so as to satisfy the sampling theorem [14]. The analogue signal obtained at the output of the antialiasing filter is sampled and coded by an analogue-digital converter. In the case of sound signal sampling the sampling frequency should be higher than 40 kHz. The output of the analogue-digital converter is a digital signal. Let the output of the analogue-digital converter be a signal $x(n)$. It is well known that $x(n)$ is a dimensionless set of data. It means that calibration of the measurement system is the first and necessary step before any application of the toolbox. The result of calibration should be a calibration constant K. Then the time waveform of the sound pressure $p(n)$ can be computed by expression $p(n) = Kx(n)$. In order to apply this expression for computation of $p(n)$ it is necessary for the measurement system to have a flat (constant) frequency characteristic in the whole band of frequencies corresponding to the sound spectrum.

In the case of evaluating the loudness, sharpness and critical band rate moments it is necessary to evaluate the acoustic pressure level at the particular octave or one-third octave frequency band. For this purpose the digital signal $p(n)$ is filtered by a set of octave or one-third octave pass-band digital filters. It follows from the digital filtering theory that the digital filters design as well as digital filter parameters and properties depend on the sampling frequency [14]. It means that the octave or one-third octave pass-band digital filters have always to be designed for a selected sampling frequency. In the Toolbox Psychoacoustics, the evaluation of roughness, tonality, and sensory pleasing sound is based on the algorithms described in [7, 8]. These algorithms are built up on the assumption that the sampling frequency is $fs = 40.96$ kHz. If the sampling frequency is not fs, it will be necessary to resample the signal $p(n)$ [14]. Generally, resampling of $p(n)$ can be performed by its repeated interpolation and decimation [14]. In the MATLAB environment, the m-files interp.m and decimate.m included into Signal Processing Toolbox of MATLAB can be used for the solution of this task. The algorithm of the BPQ evaluation are built up on the assumption that sound signals to be analysed are stationary. If this condition is not satisfied, the results obtained by the toolbox will not be correct.

A more detailed description of the methods applied for BPQ evaluation by Toolbox Psychoacoustics can be found in [12].

3 GEAR–BOX DATA MEASUREMENT AND ANALYSIS

Automatic and intelligent quality control and diagnostics in the field of car production is a very important task. Here, it is expected that each subsystem of the final product is tested. This approach strongly supports high reliable product production, which results also in a good position for the producer in the car market.

Gear-boxes belong to the most important of car subsystems. For their diagnostics, a number of methods are used. Here, order analysis, or order tracking analysis averaged in frequency and time domains can be given as an example. Sometimes, subjective evaluation of gear-boxes and their parts is carried out by "factory sound specialists", too. For the purpose of automatic and intelligent quality control and diagnostics, the subjective hearing sensations can be modeled using BPQs. In this case, conveniently selected BPQs corresponding to sounds generated by the tested gear-boxes or their parts can be consider to be features-indicators of tested product quality. Then, these features can be applied as a basis for product classification according to its quality. Depending on the complexity of relevant features, a simple hard decision system or a more sophisticated approach based on a neural network or expert system can be used as a classifier.

It follows from the above presented considerations that the selection of relevant features is a very important step in the automatic diagnostics system development. Here, we would like to analyse the application of BPQs as features for gear-boxes and gear-wheel pairs of gear-boxes diagnostics.

Following this intention, relevant results of psychoacoustical analysis of two experimental noise data packages are demonstrated in this section. The two following groups of products have been tested:

- new 5-stage car gear-boxes (5 pieces)
- separately tested gear-wheel pairs of gear-boxes corresponding to particular shifted gear (3 pieces).

In the next parts of these sections, measurement description of the sound signal generated by these machinery, results of their psychoacoustical analysis as well as a discussion of the obtained results are presented.

3.1 Measurement Description

The gear-boxes were tested on a gear-box test bench under nominal load at a stationary operating speed (constant revolutions per minute (RPM)) and nonstationary operating speed (run-up and run-down RPM). Because of the gear-box complexity, the 3rd, 4th and 5th shifted gears were set at the experiments, subsequently. At the measurement, microphones were placed on the left side of the gear-box. The distance of the microphone from the gear-box surface was above 10 cm. A 16-bit sigma-delta analogue-to-digital converter at a sampling frequency of $fs = 44.1$ kHz was applied for sound signals digitising. All gear-boxes were tested approximately at the same working conditions. For the psychoacoustical analysis, stationary data obtained at constant RPM were used. The quality of the tested gear-boxes were evaluated by "factory sound specialists".

The gear-wheel pairs were tested on a special machine developed and usually applied for the purpose of gear-wheel pair diagnostics at constant RPM by idling, it means without loading. The distance of the microphone from the gear-wheel pair was above 10 cm. A 16-bit sigma-delta analogue-to-digital converter at a sampling frequency $fs = 48$ kHz was applied for sound signals digitising. All of the shaft-wheel pairs were tested approximately at the same working conditions. Here, the quality of the tested machinery was determined by "factory sound specialists".

The relevant results represented by sets of BPQs concerning the above mentioned measurements are presented in Table 1 and Table 2. The BPQs given in the tables were evaluated by Toolbox Psychoacoustics. In the tables, the noise and psychoacoustic parameters are completed by subjective evaluation of the quality of the tested machinery. Here, the quality is defined by "factory sound specialists". "Factory sound specialists" could be considered to be trained ears in the case of analysed sounds.

3.2. Result Discussion

It can be observed from Table 1, that A-sound pressure level ($\mathbf{L}_A$), C-sound pressure level ($\mathbf{L}_C$), loudness ($\mathbf{N}$) and loudness level ($\mathbf{L}_N$) could not be applied as simple relevant features for quality diagnostics of the tested gear-box set. It follows from the fact that there are the measurement results where the tested gear-boxes were evaluated subjectively by "the factory sound specialists" as the gear-boxes of non-standard quality. It means that "the factory sound specialists" were not able to evaluate the tested gear-box as a good or bad one (in the case of these measurements, the lower values of $\mathbf{L}_A$, $\mathbf{L}_C$, $\mathbf{N}$ and $\mathbf{L}_N$ were usually obtained). This fact results probably from the complexity of the sound generated by a gear-box at particular shifted gears (special conditions for masking effect, presence of complex tooth-frequencies corresponding to the particular shifted gears, *etc.*). In order to obtain reliable results from the point of psychoacoustical analysis, more measurements with unambiguous subjective evaluation of the "factory sound specialists" are necessary.

Based on the inspection of Table 2, it can be observed that $\mathbf{L}_A$, $\mathbf{L}_C$, $\mathbf{N}$, $\mathbf{L}_N$ and sharpness according to Aures (**Sha**) could be applied as relevant features for shaft-wheel pair diagnostics. Here, it can be seen very clearly that the greater the value of these quantities the worse the quality of the shaft-wheel. It follows from these results

Table 1. Representative results of the psychoacoustic analysis of car gear-boxes

Nr.GB & shifted gear (sg)	**RPM** (min^{-1})	$\mathbf{L}_A$ (dB)	$\mathbf{L}_C$ (dB)	$\mathbf{L}_N$ (phone)	**N** (son)	**SHa** (acum)	**SHz** (acum)	**R** (asper)	**T** (tu)
GB1-3sg	3000	88.42	90.85	103.82	84.51	2.31	1.58	0.59	1.07
GB3-3sg*	3000	87.12	89.02	102.37	75.45	2.20	1.56	0.41	1.05
GB4-3sg	3000	88.06	90.13	103.30	80.46	2.30	1.57	0.57	1.07
GB5-3sg*	3000	86.89	89.63	102.53	76.25	2.24	1.58	0.40	1.07
GB6-3sg	3000	87.25	89.35	102.58	76.55	2.15	1.51	0.40	1.14
GB1-4sg	3000	89.65	90.12	104.58	90.12	2.52	1.69	0.32	1.15
GB3-4sg	3000	88.74	90.22	103.62	82.28	2.43	1.64	0.47	1.07
GB4-4sg*	3000	87.73	89.41	102.92	78.34	2.30	1.59	0.35	1.10
GB5-4sg	3000	89.68	90.26	103.89	83.78	2.56	1.69	0.31	1.14
GB6-4sg	3000	88.78	89.95	103.26	80.21	2.35	1.61	0.41	1.14
GB1-5sg*	2500	87.68	91.52	103.25	89.72	2.55	1.80	0.46	1.19
GB3-5sg	2500	88.10	88.01	102.21	74.60	2.47	1.74	0.39	1.12
GB4-5sg*	2500	87.56	87.74	101.64	71.72	2.31	1.66	0.41	1.18
GB5-5sg*	2500	88.93	88.54	102.42	75.71	2.53	1.77	0.42	1.14
GB6-5sg	2500	89.69	89.29	102.68	77.05	2.39	1.67	0.52	1.13

* the tested gear-boxes were evaluated subjectively by "the factory sound specialists" as the gear-boxes of non-standard quality.

Table 2. Representative results of the psychoacoustic analysis of shaft-wheel pairs

No. of shaft-wheel pair	**No. of teeth**	$\mathbf{L}_A$ (dB)	$\mathbf{L}_C$ (dB)	$\mathbf{L}_N$ (phone)	**N** (son)	**SHa** (acum)	**SHz** (acum)	**R** (asper)	**T** (tu)
1	34/45	93.27	92.36	107.13	104.89	3.85	2.27	0.19	0.98
2	34/45	95.55	94.42	108.79	117.74	4.34	2.41	0.17	0.83
3	34/45	99.43	97.99	110.52	132.70	4.70	2.41	0.26	1.03

Note: according to "factory sound specialists" expression, the shaft-wheel pair of No. 2 was worse than that of No. 1 and No. 3 pair was the worst one.

Legend:

$\mathbf{L}_A$ A-weighted sound pressure level measured in accordance with IEC 651 in (dBA)
$\mathbf{L}_C$ C-weighted sound pressure level measured in accordance with IEC 651 in (dBC)
$\mathbf{L}_N$ loudness level calculated according to ISO 532 in (phone) / in ISO it is marked P/
N loudness calculated according to ISO 532 in (son) / in ISO it is marked S/
SHa sharpness of sound calculated according to Aures in (acum)
SHz sharpness of sound calculated according to Zwicker in (acum)
R roughness of sound calculated according to Aures in (asper)
T tonality of sound calculated according to Terhardt in (tu)

that $\mathbf{L}_A$, $\mathbf{L}_C$, $\mathbf{N}$, $\mathbf{L}_N$ and **Sha** can be applied with success for shaft-wheel pair diagnostics. It can be seen from Table 2 also that there is very small or no correlation between the gear-box quality and sharpness according to Zwicker, roughness and tonality. With regard to this fact it can be concluded that these BPQs cannot be applied as relevant features for shaft-wheel pair diagnostics.

With regard to the previous discussion and taking into account the results given in Table 1 and Table 2, the following general conclusions can be accepted:

– A gear-box is a very complicated mechanical system. With regard to this fact, some of BPQ can be applied as a feature for gear-box diagnostics. In order to solve this problem, an integral approach based on a neural network classifier [15] could be applied for that purpose.
– Gear-box quality recognition using BPQs requires more data from a statistically relevant number of tested gear-boxes with well-defined attributes for satisfactory and non-satisfactory states. This approach would allow to design classifiers based on neural networks. Then, the neural network based classifiers would be applied for classification of the tested gear-boxes. An example of this approach can be found *eg* in [16].
– Psychoacoustical methods could be applied with advantage as additional methods for gear-box and shaft-wheels pairs diagnostics, too. Here, order analysis, order tracking analysis averaged in frequency and in time

domains, higher-order order spectra analysis, *etc*, are applied as very important methods.

- A shaft-wheel pair is not a very complicated mechanical system. It follows from the previous discussion as well as from Table 2 that BPQs can be directly applied for shaft-wheel pair diagnostics with success.
- Gear-box equipment quality control and diagnostics assumes team-work and specialists co-operation, with designers, specialists in technology and signal processing engineers equipped with corresponding knowledge, measuring apparatus, and software.

4 CONCLUSION

In this paper, psychoacoustical analysis of car gear-box noise as well as noise generated by shaft-wheel pairs of gear-boxes is presented and discussed. The task solved in this paper could be considered to be a case study. It follows from the obtained results that the psychoacoustic could be a useful tool in the field of diagnostics of sound generating systems. In some task, the BPQ application for the purpose of diagnostics could be relatively simple and successful (*eg* shaft-wheel pair diagnostics), in other cases this approach could be at least very complicated (*eg* gear-box diagnostics). With regard to the results and experience obtained in the field of psychoacoustic applications, and taking into account the knowledge concerning the possible tasks to be solved by BPQs applications, we believe that psychoacoustics will be a reasonable and powerful tool in the field of non-destructive methods of sound generating system diagnostics.

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