Malfunction or Normal Operation? Evaluation of the Subjectivity of Noise and Vibration Phenomena Accompanying the Operation of Motor Vehicles

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Abstract. In the age of modern automotive diagnostic instruments and automotive on-board computers, the human ear is still the benchmark for detecting and judging certain automotive noise phenomena. The human ear is an extremely sensitive, versatile "instrument," but it does not provide information that can be stored and processed later. The sense of hearing it evokes is subjective, often different from person to person, even for the same noise/sound. Therefore, it is not possible to determine certain defects that provide a more differentiated acoustic pattern using the human ear alone. This publication deals with the comparison of measurable results and subjective impressions. For that purpose, noise measurements were performed on two different passenger vehicles, and psychoacoustic parameters (loudness, roughness, sharpness) and in addition the overall sound pressure level were evaluated. Based on the analysis, it can be stated that the evaluated psychoacoustic parameters can judge the perception of disturbing noise phenomena. So, the claims of the passengers can be strengthened through the psychoacoustic analysis.

Keywords: Transmission · Diagnostics · Psychoacoustics · Noise · Vibration

1 Introduction

In our days, the sales of passenger vehicles have steadily increasing tendency worldwide. Among other components, every car contains a powertrain, including the gearbox. Even electric cars can have gearbox, which is the most important and expensive parts of the cars. Depend on the type of failure the repair costs can be very expensive, especially in case of automatic transmissions (planetary, DCT, CVT). Regarding to older vehicles the needed repair could mean a financial loss. The investigation of the malfunction in the gearbox could also mean cost saving. Strange noise or unusual vibration that come from a certain component of the car may indicate a fault for the customer. For example, grinding/squeaking sound can indicate that the transmission fluid is on a low level or brake pads are worn out. However, an awkward noise does not mean necessarily that

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something is wrong with the vehicle. The human sound perception strongly subjective. For some people, a specific noise is annoying, while the others do not even notice it. The sensation depends on many parameters, such as spatial distribution and time structure of sound, noise duration, sound level, subjectivity etc. The scientific study of sound perception and audiology is psychoacoustics. At this point arise a question what acoustic phenomena can be considered as a failure noise? Is it possible to make decision without objective measures? Last, but not least, what kind of relations are between the objective fundamental measurements used in diagnostics and psychoacoustical values? To answer these questions the human centered subjective concepts, like sharpness – roughness should be transformed into objective concepts, which are measurable and properly describe the human judgement of noise. That is what psychoacoustic partially do. After these establishments, the task is now that involve the psychoacoustic assessment criteria (loudness, harshness etc.) in failure diagnostics in order to make decision about a certain noise problem from customer point of view.

2 Psychoacoustics

Psychoacoustics is a branch of science dealing with the perception of sound, the sensation produced by sounds and the problems of communication. The question of psychoacoustics is that what kind of relationship is between sensory perception and physical variables. Figure 1 shows the correlation between objective measurements based on physical parameters and subjective concepts. Strictly speaking, it represents the concept of psychoacoustics through one picture.

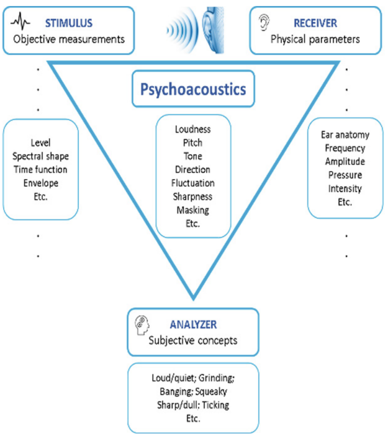

Fig. 1. The concept of psychoacoustic

Hearing is not purely a mechanical event but a perceptual phenomenon. Inside the inner ear the mechanical sound energy transforms into biological signals. In the physical world every sound is affected by the encoding and transmission characteristics of the auditory nervous system. High-level frequency – and temporal resolution is provided by the encoding process during transduction. The sound is transformed in many ways while it passes through the outer and middle ear (Fig. 2).

In nutshell these events of the auditory system are responsible for our acoustic perception of the world around us. The field of psychoacoustics is much wider than we could discuss about it in few pages. Research and concepts as frequency selectivity and masking, perception of loudness, timbre, pitch, localization of sounds or temporal processing in the auditory system require more attention [0].

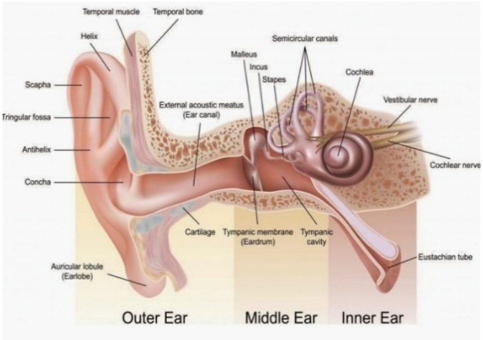

Fig. 2. Structure of the human ear: outer, middle, and inner ear [2]

The limitations of A-weighted sound level measurement became clear more than 30 years ago in the automotive industry, when the sound quality of interior and exterior noise in motor vehicles was to be improved. The A-weighted sound pressure level is only a very rough approximation of the loudness perception. Moreover, a low noise level does not equate to acoustic ‘well-being’.

Noise can not only impair a product but also benefit it. The sound of an automobile door closing is a classic example that has been studied for many years. The aim of these investigations was to generate a door closing noise that suggests a solid car door. (Remark: the geographical region where the people live also have an effect on it.) Today, the term “noise quality” or “sound quality” summarizes the endeavour to use technical freedom in the development of a product in such a way that the resulting noise matches the product as well as possible. A hearing-friendly sound analysis with the help of psychoacoustic measurement technology is essential.

A disproportionate number of high frequencies conveys a close and “aggressive” sound source that compels increased attention from the listener. Such a noise attribute, which is usually undesirable, can be measured using the psychoacoustic variable “sharpness”. If a low-frequency component is added to a “sharp” sound, the sharpness can be reduced. However, the newly created sound is louder, but is often perceived as “less annoying” or “less disturbing”.

However, periodic fluctuations in the envelope of a signal or the frequency can also lead to a noise being judged as “dissonant” or “unpleasant”. In addition, periodic fluctuations in the envelope can also indicate disturbances in the smooth running of a machine. Psychoacoustic measurement technology is therefore not only suitable for optimizing noise quality, but also for acoustic quality control or system monitoring. However, psychoacoustic parameters can no longer be determined using an elementary sound level meter, but require a time-dependent, narrow-band signal analysis.

In the present days a branch of "classic" psychoacoustic parameters is established, e.g., loudness, sharpness, roughness, tonality, fluctuation strength, in addition, numerous other hearing-related variables and parameters are known that are also often used. Next, we short introduce a few of them (based on [3]):

a. **Loudness**: The psychoacoustic parameter loudness reflects the subjectively perceived loudness of sounds. The loudness scale is calculated using psychophysical ratio scaling, based on relative judgments. The loudness scale was developed to represent human perception of loudness on a linear scale. The reference signal, a sinusoidal tone with a frequency of 1 kHz and a sound pressure level of 40 dB, has a loudness of 1 sone. Since this is a ratio scaling, the loudness corresponds to twice as loud perceived signals 2 sone. E.g., if 40 phon = 1 sone, then 50 phon get the value 2 sone, 60 phon get the value 4 sone, 70 phon get the value 8 sone etc. Accordingly, the loudness indicates by how many times louder a sound event is perceived on average in comparison to another sound event. Loudness is considered an essential parameter in the area of sound quality
b. **Sharpness**: The psychoacoustic parameter "sharpness" refers to the perception of sounds, whose energetic focus is in the high-frequency range. These are often described by listeners with attributes such as "sharp", "shrill" or "bright". A narrow-band noise ($\Delta f \leq \Delta f_G \approx 160$ Hz) with a center frequency of *1* kHz and a sound pressure level of *60* dB is therefore assigned a sharpness of *1 acum* (acum = Latin for sharp). Sharpness is standardized in DIN 45692.
c. **Roughness**: The psychoacoustic parameter roughness describes a sensation caused by modulations in a sound event. The impression arises if there is a time-variant envelope within a frequency group, i.e., if for example, tones have a temporal structure due to the permanent change in amplitude or frequency. A 1 kHz tone with a level of *60* dB, which is amplitude-modulated with a modulation frequency of $f_{mod} = 70$ Hz and a modulation depth of $m = 1$ (reference sound), is assigned the roughness $R = 1$ asper (lat. rough).
d. **Fluctuation strength**: The psychoacoustic parameter fluctuation strength describes the perception of "slow" modulations. The fluctuation reflects the perception experienced when the signal fluctuates at very low modulation frequencies. Sounds modulated at 20 Hz and below are perceived as "fluctuating".
e. **Tonality**: Tonality is another one-dimensional psychoacoustic parameter that can be perceived isolated. A noise is considered tonal if individual tones or tonal components are clearly perceptible. Narrowband noise is often perceived as having tonal content as well, but this effect diminishes significantly as the bandwidth increases.

3 Problem Description and Measurements

In this paper, we focus on acoustic problems in two different vehicles, which show the difficulties of distinguishing between normal operation noise and failure noise. The outline of these acoustic problems will be described in this chapter.

3.1 Problem 1: Impact/hit Noise of a Manual Gearbox

It was the first time, when we met with the problem of human subjectivity regarding noise perception during diagnostics. An owner after 6 months of using a relatively new car (year of manufacture 2019, turbocharged direct injection, petrol engine, front-wheel driven, 6-speed manual transmission) complained about a specific noise during gear shift from gear 1 to gear 2, resp. from gear 2 to gear 3. In terms of frequency content, the noise can be described as impact or hit noise. During shifting the noise can be heard clearly inside and outside of the car. For the owner, the noise is very disturbing, while some of the passengers do not find the noise to be very annoying and someone do not even notice it. After discovering the problem several components were replaced: clutch, axle - shafts and the gearbox one after the other. Despite of the repair the noise was still existent. Therefore, our task was to analyze the problem without disassembling the gearbox [4].

To make sure the noise is existent and identify the noise characteristics a pass-by noise measurement was performed. The test could not meet the ISO 362 - 1 to 3 since we do not have the proper pass-by noise test facility and in addition a gear shift had to be performed during the acceleration. Acc. to standard a fixed gear must be used during the acceleration. Nevertheless, we managed to perform measurements as close as possible to the standard. The car was started from stillstand in gear speed 1 and was driven on an approximately 30 m long road with one lane while the driver shifted to gear 2. The pass-by sound pressure level was recorded during several measurements and the noise phenomena could be reproduced every time.

To get closer to the malfunction a static state measurement of the car was also performed. The car moved onto a lifting platform and the engine-gearbox unit was moved back and forth by hand against the pendulum support. At this movement a sharp impact/hit noise could be heard, as something might be loose inside the gearbox. On the gearbox housing accelerometers were mounted to measure the vibration and a near field microphone to record the sound pressure. The resulted noise was very similar to that we observed during pass-by noise measurement. The measurements were taken separate for the measurement points, due to the lack of a multichannel DAQ system.

3.2 Problem 2: Whistling Noise of an Automatic Gearbox

An upper-class second-hand AWD saloon car (mileage approx. *200.000* km) with diesel engine and automatic gearbox (with hydrodynamic torque converter) is given where the new owner complains about a whistling noise driving in reverse gear. The noise can be heard by accelerated ride, by creeping at idle engine speed and by braking from creeping to stillstand. The noise is like an electric motor noise, but there was no electric motor in the drivetrain of the car. Another possibility is the gear wine noise from the reverse gear wheels. The car was bought a short time before the investigations, it is not known if the noise problem was known before. The seller didn't want to provide information about it. Nevertheless, the whistling noise was very annoying and worrying for the new owner, and if there is really a malfunction, it implies a warranty claim towards the seller. So, the problem had to be investigated systematically.

For that purpose, interior noise measurement was performed several times at the front passenger head position, in driving conditions which represented the disturbing noise. The measurements contained the following driving phases (only in reverse gear): acceleration, rollout, creeping and braking. Later the microphone raw time data was post-processed and analyzed.

Furthermore, we tried to obtain drawings, exploded view, the power flow scheme of the gearbox, resp. information about the gear types, number of teeth of the reverse gears, but only a single3D drawing could be found, which was unfortunately not particularly helpful for the analysis and in addition the gearbox could not be disassembled.

4 Analysis

4.1 Analysis of Impact/hit Noise

For the first analysis the averaged spectrums and spectrograms were created by Fast Fourier Transformation from the pass-by and standstill measurements based on the raw time signals. The analysis aims to find frequency contents which may refer to the failure. Figure 3 shows the spectrogram of the pass-by noise [4].

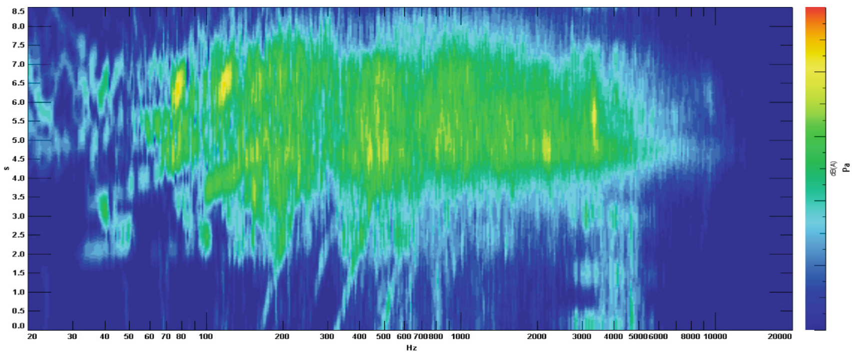

Fig. 3. Colourmap of the pass-by noise measurement

The frequency range of the noise phenomenon is approx. *4000* Hz wide and there are only a few frequency peaks (at *2000* Hz and *3000* Hz) that might refer to a certain component of the gearbox. Overall based on the pass-by noise we could not identify any faulty component in the gearbox. Nevertheless, this measurement, respectively its replay and listening were able to highlight the existence of the disturbing noise phenomena. We did further investigations at standstill condition, which result can be seen in Fig. 4. The figure shows the raw time signal of standstill measurements. The time signals have almost the same curve progression, the distinct peaks clearly indicate the presence of impacts. However, the localization of the failure was also not possible based on this information.

Next let us look on the human perception of that impact noise. As it was already mentioned, the owner finds that gear shift noise very annoying, but other persons did not

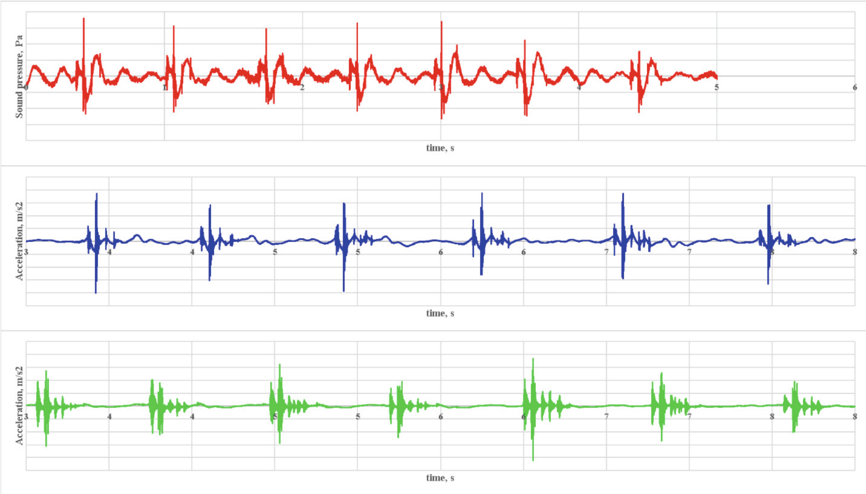

Fig. 4. Time signals at the standstill measurements (top: sound pressure, mid: acceleration point 1, bottom: acceleration point 2). (The recording of the 3-time signals was not performed synchronous.)

even notice it. We investigate first the pass-by noise measurement regarding psychoacoustical parameters, which could explain the grade of annoyance of the listeners. We investigate the psychoacoustical parameters *loudness* (based on Zwicker), *roughness* and *sharpness* and as comparison the A-weighted overall sound pressure level (SPL(A)). In the following few paragraphs we give a short overview of the calculation of these three psychoacoustical parameters, and after that we introduce our calculation results based on the pass-by and stillstand noise measurements:

- In addition to sound pressure level and frequency, loudness also depends on the bandwidth of a signal. An increase in bandwidth leads to an increase in loudness if the frequency range of the sound event exceeds the frequency group width (critical bandwidth). This is considered in the loudness calculation method of Zwicker, which schematic workflow is shown in Fig. 5. The excitation level and critical band rate (CBR) patterns are transformed into specific loudness in a first step. This transformation is based on Stevens power law by assuming a power function with a fixed exponent and a pitch-dependent basic excitation. Finally, the overall loudness is obtained by integrating the specific loudness over the frequency groups. The method is standardized and described in ISO 532B.

- According to v. Bismarck a single numerical value of the weighted loudness- critical band rate pattern (CBR) is calculated. Finally, the weighted total loudness is divided by the total loudness. The ratio is a measure of the perception of sharpness. The reference sound is marked by a cross in Fig. 6.

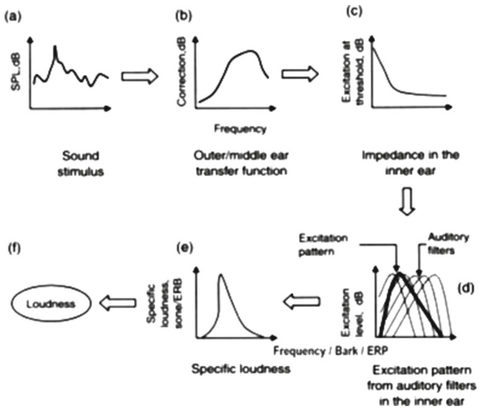

Fig. 5. Schematic diagram of the various steps in Zwicker's loudness model [5]

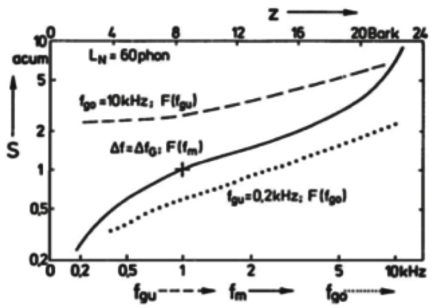

Fig. 6. The sharpness of narrowband noise (solid), low-pass noise (dotted), and high-pass noise (dashed) as a function of center frequency f_m, upper cutoff frequency f_{go}, and lower cutoff frequency f_{gu}, respectively. The cross marks the reference sound with a sharpness of 1 acum [6]

- The perception of roughness is particularly pronounced in frequency and amplitude modulated tones. On the other hand, there is no strong dependency on the sound pressure level. Only an increase in the sound pressure level of around *40* dB causes the roughness to double. The figure shows the dependence of amplitude-modulated tones on the degree of modulation m, the modulation frequency f_{mod} and the frequency f_c of the tone

Based on the methods shown above, and described in the related literature, we performed the calculations. The results are shown in Fig. 8 for the pass-by noise.

As can be seen on Fig. 8 (top left/red) the trend of the overall SPL can be compared with the colourmap in Fig. 3. The loudness curve (top right/blue) also has similar trend to the overall curve (not surprisingly). In both cases, the maximum values are reached between *5* s and *7* s, because in this time range the vehicle is the closest to the microphone. The sharpness (bottom right/brown) shows that the noise is not particularly sharp, and the sharpness stays quite similar during the measurement time. The roughness (bottom

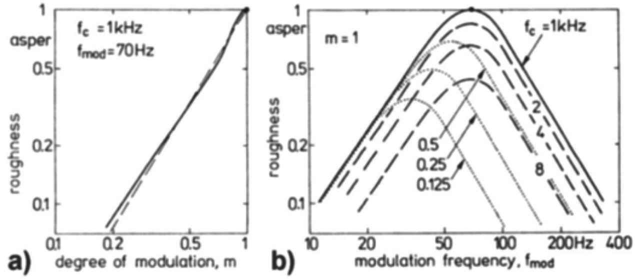

Fig. 7. Roughness (R) of an amplitude modulated tone depends on the degree of modulation m (part a) and the modulation frequency f_{mod} (part b). In part b the carrier frequency f_c is varied as a parameter [7]

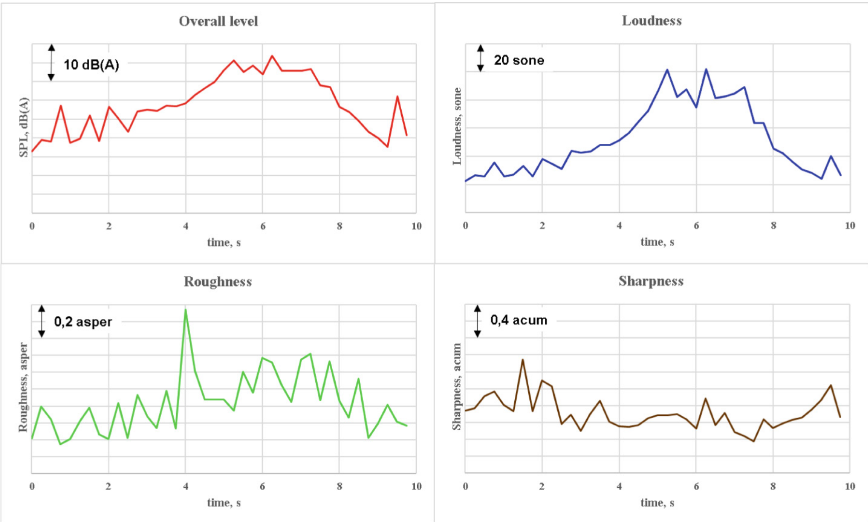

Fig. 8. Calculation results of 3 psychoacoustic parameters plus overall SPL based on the pass-by noise signal

left/green) shows in contrast that the noise is increasingly rough with the maximum value at approx. *4* s of time. This time value marks exactly the start of the gear shift process. So, the gear shift noise could really mean a certain disturbing effect on the human perception in some cases, where the persons are sensitive for that type of noise modulation.

Figure 9 shows a similar diagram as Fig. 8, but now with the standstill noise measurement. In this case, the motor-gearbox unit (queer built-in) was rhythmically moved forwards and backwards by hand and that is shown in the raw time diagrams in Fig. 4 (top diagram). This signal characteristics can also be found in Fig. 9 top left (red) curve which is also representing the overall level during the measurement. Regarding loudness, sharpness and roughness can we state almost the same as already written in the latter paragraph. So, there is a good agreement of the conclusions between the pass-by and standstill measurements regarding the calculated psychoacoustical parameters.

The gear shift noise by the pass-by noise measurements and the standstill noise measurements are both rough noises that are capable to cause disturbance by persons in certain amount.

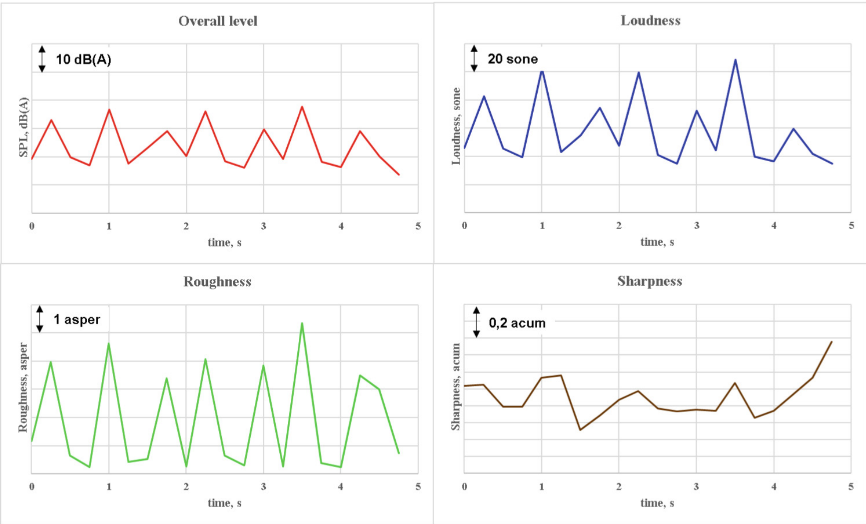

Fig. 9. Calculation results of 3 psychoacoustic parameters plus overall SPL based on the standstill measurement signal

4.2 Analysis of Whistling Noise

In the post-processing of the raw time signal the spectrums and spectrograms were produced with the help of Fast Fourier Transformation in the same manner. The goal is to find evidence which is refer to the failure. Figure 10 illustrates the frequency content of time signal of sound pressure in reverse gear speed. The red coloured markings show the changing of frequency content and sound pressure level in correlation with the motion of the car.

In the low frequency range *3rd*, *6th* and *9th* order of the ignition noise appeared. After a certain speed of the car the noise originated from the ignition is not significant anymore, since the car is not accelerating any more, the load is reduced. In the higher frequency range between *500* Hz and *4000* Hz one can clearly see the increased level of sound pressure when the car is accelerating, then creeping and finally stopping. On the other hand, during rolling, the noise disappeared. After the car was accelerated for *8* s, due to the mechanical energy loss of the motor the velocity started to decrease.

However, because of the momentum, the car was still moving for a while without energy investment, roughly for additionally *10* s. Near idle speed the car reached the creeping phase. After that the car was stopped with the brake pedal under *2* s. This chart shows us that, the whistling noise only occurs, when the transmission is under load, but only in reverse gear.

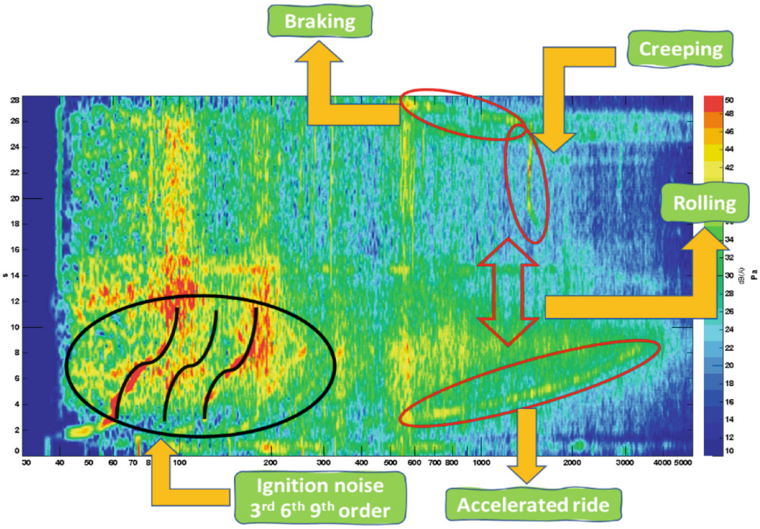

Fig. 10. Interior noise in reverse gear speed

The calculation of the psychoacoustic parameters was also done for the raw time signal similar as already described in chapter 4.1. Due to the longer time signal (approx. *30* s) we took relevant time ranges which were related to significant phases of the ride:

- *0–8, 5* s: acceleration phase from stillstand
- *10–18* s: rollout phase from max. speed to creeping speed
- *20–26* s: creeping phase at idle engine speed

In Fig. 11 the calculation results are shown for each calculated psychoacoustical parameters and for each significant ride phase. The results show on the top left (red and blue curves) and top right (red and blue curves) diagrams, that for the accelerating and for the creeping phase (in both is the whine/whistle noise present) the overall SPL and the loudness have lower levels as in the rollout phase where no whistle/whine noise is present.

Regarding the roughness it can be stated that the noise in the investigated ride phases is not rough, and the three curves are almost on the same level. The sharpness is in case of accelerating (bottom right red curve) and creeping (bottom right blue curve) is distinctly higher than in roll-out phase. So, the results meet well with our expectations that a whine/whistling noise has higher frequency contents, thus it is sharp and could be disturbing for some people too.

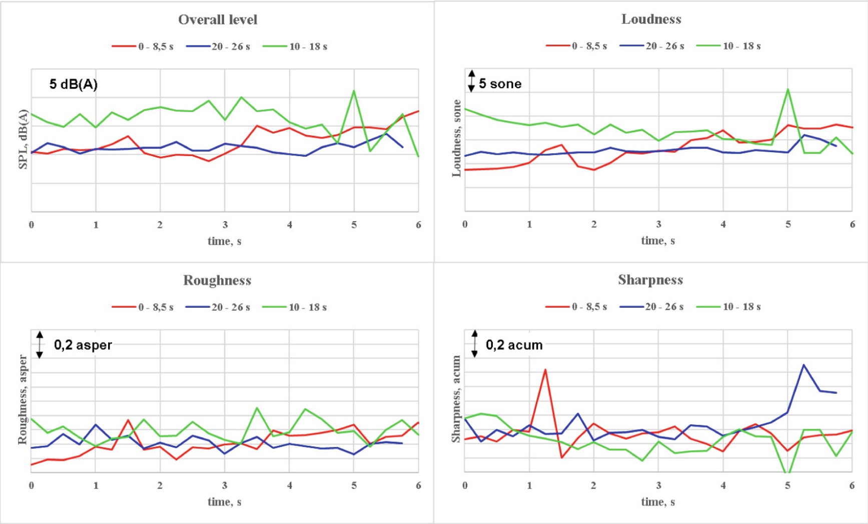

Fig. 11. Calculation results of 3 psychoacoustic parameters plus overall SPL based on the interior noise measurement for 3 ride condition

5 Conclusions

Present article illustrated, based on real-life acoustic problems on motor vehicles the difficulties of the characterization and judging of noise phenomena. Due to the lack of detailed information about the gearbox components in both presented cases, unfortunately it was not possible to exactly define whether a failure or a normal operation noise occurred. We can only presume that in the first case (gear shift noise) the occurred noise did not result from a mechanical fault, the gearbox and the gear shifting mechanism worked well. In the second case (whine noise) we can rather interpret the occurred noise as a fault noise since upper class (almost luxury) car must not produce such a noticeable noise.

With psychoacoustic investigations could be proved in both cases that the noises can be really perceived disturbing. In the first case the noise was rather rough, in the second case it was rather sharp. The claims of the owner were reasonable. Unfortunately, the objective of the investigations could not be fully reached due to the lack of important details about the gearboxes, nevertheless, the investigations will continue.

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