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Measurement and assessment of noise caused by vehicle brake systems

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ABSTRACT

During the last years the overall sound level inside of modern vehicles continuously descended. In consequence an increasing variety of low level noises is not masked any longer. A specific noise, however, can lead to annoyance of the driver, even if its level is low. Thus customers frequently claim about sound quality problems. While the customers' request on performance and durability of brake systems increases, naturally causing increased noise propensity, the sensitivity towards brake noise increases in-parallel.

As a result of rising customers' claims and expectations, car manufacturers and brake system suppliers started to extend the scope of their performance and durability tests for acoustical examinations. Up to now these examinations focus on the perception of brake noises inside the car. But since brake noise can attract the attention of potential customers, also the reduction of exterior noise emissions is of rising importance. Additionally, among the various vehicle sounds brake noise plays an important role for the overall acoustical environment pollution. Hence the reduction of these noises is of high common interest.

In this paper typical interior and exterior brake noises and their sources are described. Test procedures are presented which include technically challenging procedures for the automated detection and assessment of typical brake noises.

1 INTRODUCTION

It is well known that squeal noise of refined brake systems is very sensitive to specific vehicle operations. Efficient brake noise engineering is capable to remove all systematic noise phenomena which are easy to reproduce. The remaining problems are difficult to grasp and show statistical occurrence due to the complicated boundary conditions which must be fulfilled inside the brake system to enable sound excitation. Therefore it is common in the automotive industry to use long-term vehicle tests for both pre-conditioning of the brake and noise search. Initially, noise search was done subjectively by use of rating scales. During the last years measurement systems have been developed to support noise assessment with objective data. Strategies of evaluation and performance of available systems are quite different. Better understanding and alignment of procedures, however, can help to determine statistical validity of test routes and enable correlation to dynamometer tests. Only few data regarding the correlation of different test route results have been published (e.g. [1]).

Subjective noise search needs specific exterior conditions, like reflecting walls or alleys to reflect exterior brake noise to the driver's ears. Subjective evaluation strongly depends on driver training. Evaluators must well know how to perform driving operations and how to apply values of a rating scale. Subjective evaluations can show a high variability while long

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road drives with relatively rare noise occurrence have to be rated. A clear and reliable noise statistics is required instead, which can only be provided by sophisticated measurement systems. Another disadvantage of subjective evaluation is that localization by hearing is limited in case of pure (sinusoidal) tones [2]. Especially the allocation of a noise excitation to

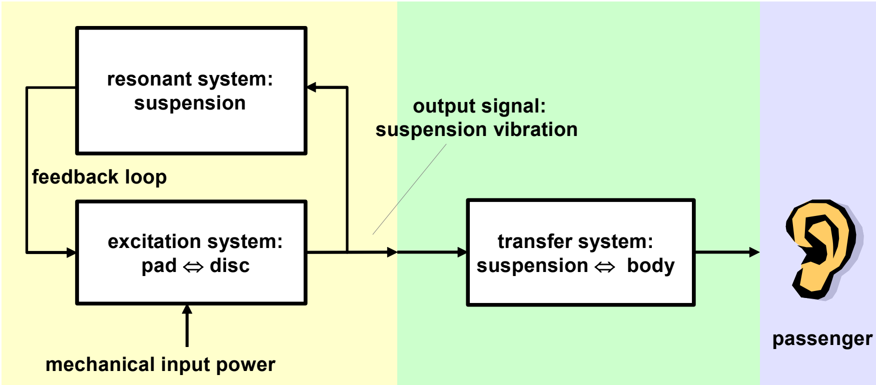

Figure 1: General system description of the feedback from brake and suspension to the excitation mechanism of brake noise in case of self-excitation.

front or rear axle is of importance regarding the different behavior of both axles and due to the fact, that different component suppliers are often responsible for front and rear.

System for appropriate measurement of brake noise must be based on noise detection with standardized features, leading to search results which are highly correlated to subjective (i.e. psycho-acoustic) parameters [3].

2 TYPES OF BRAKE NOISE

In general, brake noise phenomena can be distinguished by the mechanism of excitation. A simple rubbing of particles of disk (or drum) and friction material towards each other usually generates a broad-band random noise. The most annoying pure tone phenomena like brake squeal and moan, however, are based on non-linear processes of self-excitation with distinct feedback of energy.

The broad band *friction noise* which is perceivable inside the passenger's compartment can show various bandwidths. Its spectrum is shaped by a variety of noise paths, leading energy to sound radiating panels from which air-borne sound reaches the ears of driver and passengers. It is also audible exterior of the vehicle, but its magnitude is usually less than that of brake squeal. If it contains some tonal components, generated by narrow-band filtering due to specific resonances, it is named *wire-brush noise*.

The onset of self-excited vibrations normally results in very high amplitudes which are clearly perceptible both in the passenger compartment and outside the vehicle and can greatly impair driving quality. A self-excited system results when the energy introduced due to dynamic forces is fed back to the location of excitation and supports the continuation of the excitation process (Figure 1). The excitation is induced by dynamic forces at the contact surface between friction material and disc or drum. This is caused while the friction interface changes from static to dynamic friction (stick-slip-phenomenon). These forces cause attached components to vibrate, and they in turn feed back a part of the vibration energy to the interface of pads and disc/drum. This energy puts the excitation system into a state in which additional rotational kinetic energy is induced. The self-excited process thus results in complete compensation of the system’s internal damping mechanisms (*negative damping)*. This enables very high vibration magnitudes, which cause sound radiation with strong sound pressure levels.

Creep groan is a typical low-frequency vehicle noise with fundamental frequencies at 50-200 Hz [4]. It arises when vehicles with automatic transmissions start off and the service brake is slowly released. It can also be provoked with release of operation brake or parking brake while standing on a ramp. Although creep groan is excited by a stick-slip phenomenon in-between friction material and disc, the self-excitation is mainly driven by resonances of various axle components. Especially at low brake temperatures, it shows a large number of harmonics (Figure 2).

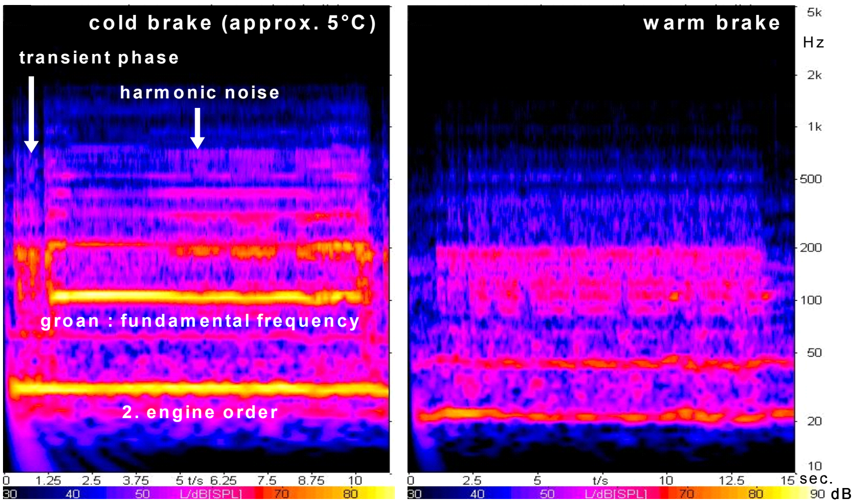

Figure 2: Spectral analysis of creep groan with cold and warm brakes (vertical axis: frequency [Hz]; horizontal axis: time [sec]; color scale: sound pressure level [dB]).

With increase of frequency, self-excitation leads to pure tones with no or only few audible harmonics (Figure 3). Sound pressure levels and grade of annoyance, however, are high. Therefore phenomena like *moan* (at 200-500 Hz) and *squeal* (1 – 16 kHz) need specific attention of brake optimization. In general it can be stated that with increasing frequency the contribution of vibration components more and more focuses on the interface between pads and disc/drum. While brake moan is still sensitive to the modal behavior of knuckle and suspension arms, a high frequency squeal in most cases exclusively depends on the properties of caliper, brake pad, and disc.

While at high frequencies the distribution of energy via structure-borne sound is strongly reduced by sound-package material, sound radiation at the brake itself is of major interest for noise engineering. The propagation into the exterior space is not significantly reduced by obstacles and sound barriers. High-frequency exterior noise reaches the listener with high levels and easily catches the attention of pedestrians. Assessment and reduction of both, interior and exterior noise is therefore highly recommended for optimization of the overall vehicle sound quality.

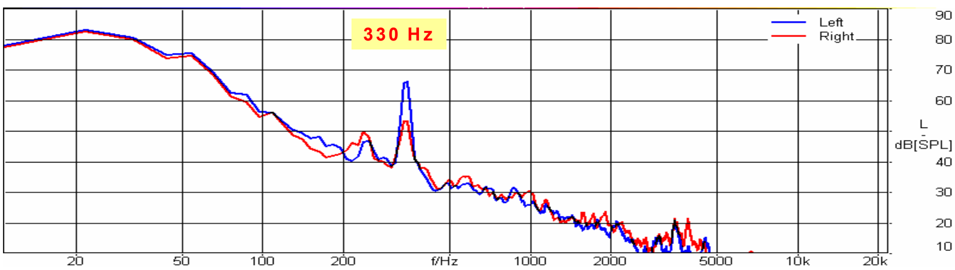

Figure 3: Spectral analysis of a pure tone brake noise, e.g. brake moan at 330 Hz

3 STRATEGIES OF BRAKE NOISE ASSESSMENT

The application of noise measurement systems for brake noise optimization depends on the principle strategy (Figure 4). If focused on perception of driver and passengers or of people outside the car, it must enable evaluation of psycho-acoustic parameters and estimation of annoyance. If focused on acoustics and vibration properties of the brake components, it must provide physical data appropriate for functional optimization.

3.1 Driver focused strategy

This approach is often used to optimize brake noise and vibration as part of all perceivable attributes of the driving environment. Measurement is done by means of interior microphones. It is recommended to use two microphones near the driver's ears [5]. The noise energy excited at the brake is transferred by various transfer paths, which show complicated frequency dependence and often non-linear properties. Therefore, setting of targets for component behavior derived from interior noise requirements is a demanding task. The drivers perception is influenced by background noise, e.g. by power-train noise, wind noise and road noise. The design of the whole vehicle has influence on the balance of brake noise and background contributions. Therefore the assessment of a given brake is strongly influenced by the total system. This situation naturally is similar to subjective assessment done inside the passenger's compartment.

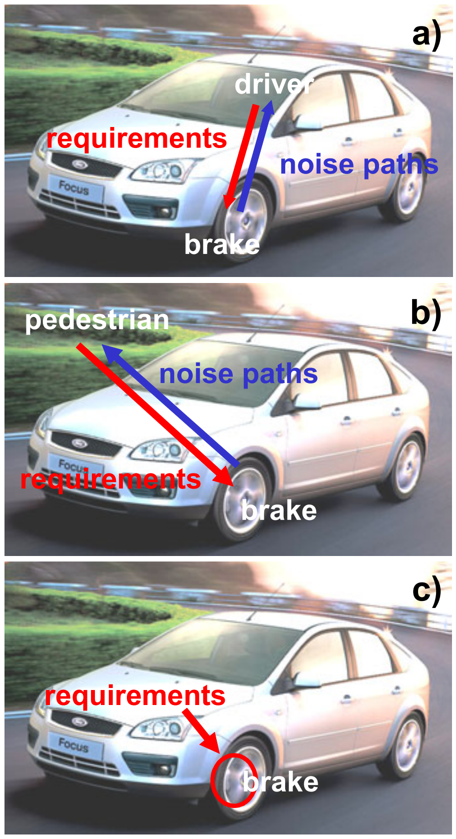

Figure 4: Principle strategies of brake noise assessment: a) driver focused; b) pedestrian focused; c) component related

3.2 Pedestrian focused strategy

With view on the exterior appearance of a vehicle, it makes sense to also consider exterior brake noise radiation. A brake noise event may attract a pedestrian's attention and may cause negative rating of the specific vehicle brand. Thus measurement or estimation of exterior brake noise is important with view on the overall brand image. Measurement requires exterior microphones at every corner, which must be robust enough to face a long-term usage under severe driving conditions. Calculation of the far-field sound parameters is another complicated issue due to unknown radiation directivity of the source [6]. On the other hand, it will be extremely difficult to measure brake noise with a microphone positioned at the roadside, while exact reproducibility of excitation can not be assumed in general.

3.3 Component related strategy

If the assessment is focused on the noise source, it is much easier to define component targets. Measurements can either be done with accelerometers or by means of near-field microphones. Results are much less influenced by other vehicle sub-systems and other noise/vibration sources. If microphones are used near the corner, the correlation of vehicle test results with those of dynamometer tests is considerably improved. Human perception, however, is excluded, and a customer-related estimation is demanding due to the aforementioned complicated transfer paths. Thus, the correlation of component measurement results to customers rating is limited. On the other hand, the data are more appropriate to understand the excitation process and to define measures of noise reduction at the source.

4 TEST ROUTES AND VEHICLE OPERATION

While the occurrence of brake noise is related to a large variety of driving conditions, measurement and assessment require a methodology that is quiet different to standard noise investigations. Only few typical brake noises like creep groan show appropriate reproducibility and thus can be investigated with respect to a fixed set of parameters. Squeal and moan of refined brake systems show a low frequency of occurrence, caused by very specific combinations of parameters. A long, realistic test route is required to find those critical conditions.

The instantaneous condition of the brake system depends on the parameters: temperature of disc/drum and friction material, brake line pressure, pressure distribution on the contact surface of friction material upon disc/drum and ambient conditions (temperature and humidity). Various parameters of vehicle operation have also influence on the squeal propensity, like vehicle velocity at start of braking, deceleration during braking action, steering angle and side forces and vehicle load conditions.

Beside the instantaneous parameters, the history of influences is of great importance. It is determined by wear of disc/drum and friction material, dust and contamination of the friction interface, profiles of vehicle usage, influence of water and humidity on disc/drum & pad material (soak) and by the temperature history (profile) before the noise occurs.

A first approach on acoustic optimization of the brake system is usually done by dynamometer tests with systematic application of parameter matrices. The total variety of conditions, however, is provided during extended tests on public roads. The driving conditions must be representative for customer usage. An appropriate test cycle can include 100-200 km and is driven during several weeks to cumulate realistic wear. With respect to a test cycle of several hours and with hundreds of brake events, but with only few noise occurrences, it is useless to record noise data continuously throughout the test. A sophisticated detection algorithm, however, can help to save evaluation time and storage capacity. Furthermore, the measurement system must record various data of brake performance to exactly define the parameter values critical for noise excitation.

5 PRINCIPLE CONCEPT OF A MEASUREMENT SYSTEM

Measurements of brake noises using representative test routes following the driver focused strategy require a specific measurement system. Although in detail the user requirements concerning the data acquisition and the automatic detection of brake noises depend on the concrete measurement task, the following principal requirements for such a system are established.

5.1 Sensors for audio signals

Following the driver focused strategy one or two cabin microphones are required anyway. At least one additional sensor for every examined brake is needed. In consequence a usual setup incorporates five or six audio channels for microphones and accelerometers. The exact position of the accelerometers depends on the brake system and the target of the examination. Further microphones may be required for additional measurements near the brakes instead of accelerometers. Sampling rates above 30 kHz are useful for these signals.

5.2 Triggering modes for the audio signals

In contrast to the recording of those parameters relevant for noise occurrences (see 5.3) the audio signals are not stored continuously during the whole time of a test drive but only sequences are recorded when the audio data are of special interest. Three cases must be distinguished:

The audio recording starts when a predefined condition in a parameter signal is fulfilled (possibly with an additional pre-trigger time) and it is stopped when a second condition rises. A typical example is that the recording takes place whenever the brake pedal has been activated or when the brake pressure is above a predefined limit. Hence, in these examples audio signals are only recorded during active brake applications.

The user gets the possibility to start and stop an audio recording manually. This mode is needed when additional recordings are required independent from the parameter signals. For example this trigger mode can be used to record audio signals during periods without brake applications. Assumed that manually triggered recordings are stored independent of the result of the detection process so also other noises can be archived that up to now cannot be detected automatically. For this trigger mode a pre-trigger time is especially useful because the driver needs it to compensate his reaction time.

Technically the most challenging method is an automated recording mode which records all signal sequences automatically that contain a relevant brake noise. This mode directly applies the detection algorithm on all incoming audio signals and stores noisy sequences only. The mode is useful especially when looking for off-brake noises that under certain circumstances can be derived from the brake system although the brake was not applied.

5.3 Parameter signals

All relevant parameters that may influence the acoustical behavior of the brakes should be recorded during the complete test drive. Because of these long recording durations these parameters are sampled with sampling frequencies below 100 Hz.

Generally during vehicle brake tests the information of the brake temperatures measured at the brake disc or the pad have to be recorded. Since in addition normally the ambient temperature is registered at least five channels are used. Type K thermocouples are the standard sensor type.

Depending on the examination task a lot of other sensors may be connected to the data acquisition system (e. g. sensors for brake line pressure, ambient humidity, vehicle acceleration and velocity, steering angle) but no further standard inputs exist. In consequence voltage channels are required in order to allow the connection of different sensor types. Some power supply voltages should be available in order to support active sensors.

5.4 System robustness

Mobile data acquisition systems for vehicle brake tests are used under challenging ambient conditions. All components must be proven for automotive environments. As test drives often are carried out within a tight time schedule the system must be installed quickly and easy to use. The system must be stable against fluctuations of the on-board battery voltage especially during the starting procedure. Short disruptions (in the range of some seconds) must be buffered. The overall power consumption must be limited to avoid too high loads for the on-board battery. Test drives are designed to check the brake system performance and possible acoustical troubles under extreme ambient conditions with the aim to disclose unknown problems. European proving grounds can be found between north Sweden and the south coast of Spain and hence the system should work between ambient temperatures ranging from -20°C to +50°C at least. The whole system must be proven to work despite of strong vibrations in the car and in dusty or moistly environments.

5.5 User interface

Data acquisition systems with automated detection possibilities are used for different tasks in the brake industry. If the system is used for development purposes, representations of a lot of the incoming signals and details about the brake noises found have to be displayed already during the test drive. In other applications, the drivers should assess the brake noises subjectively. In this case the driver's rating must not be influenced by information coming from the automatic detection running in the background. On the other hand the drivers should follow current brake pressures and temperatures nevertheless. A third application is the use of recording systems as a black box similar to a flight recorder. In this case no detailed visualization is needed at all. Only start, stop, and function indication might be visualized.

The various user requirements enumerated above clearly require configurable visualization modes. For this purpose especially touch screens are suitable offering different configured user interfaces for different tasks.

5.6 Advanced documentation

During test drives often some other data are collected, that should be stored together with the measured signals. The most important example is the subjective assessment of brake events given by the test driver. But also other subjective descriptions concerning the whole test drive or single brake events have to be registered. Since depending on the concrete task different kind of user inputs are needed, the data acquisition system must be flexible enough to fulfill these documentation tasks.

6 BRAKE NOISE DETECTION

As mentioned above brake noises occur in dependency of various parameters and hence are not easy to reproduce during realistic test drives. In consequence only a small part of all audio recordings collected during hundreds of brake events contain the problematic brake noise. Finding the relevant noisy recordings by listening into all recordings is time consuming and laborious. In addition the quality of the human detection results depends on an individual and inter-individual strongly varying subjective detection reproducibility. In order to avoid storage capacity problems the automated detection should yield results as soon as possible after the end of a brake event so that only relevant data are stored. Moreover this proceeding offers the possibility to give a fast feedback to the testing person.

Since squeal and moan are the most annoying brake noise types, existing data acquisition systems focus on the detection of these noises up to now. Thus the detection of these noise types is the topic in this chapter.

6.1 Detection based on psychoacoustics

Since only those brake noises are relevant that are perceived by the driver, the estimation of the human perception plays an important role and must be estimated during the detection process. The human perception and the simple technical description of a stimulus often deviate, especially in more complex situations. Here only more sophisticated combinations of signal characteristics are adequate to get a measure of the perception in a complex situation. One common way to find appropriate calculation methods is modeling the perception processes.

In consequence modern detection systems should work based on psychoacoustic methods [7]. Three examples for the benefit of the detection of brake noises using psychoacoustic methods are shown in the following subheadings. In these examples the *Relative Approach* analysis is used as psychoacoustic method [8].

6.1.1 Detection of brake noises in ambient noises

The detection must be robust against the difficult acoustical circumstances occurring in a driving vehicle. Noises originating from the tires, engine noises, wind noises, and noises from other vehicles aggravate the detection of squeals and moans especially for lower frequencies.

In the left part of figure 5 the spectrogram of an annoying squeal is shown. The low frequency noise floor here is dominated by tire noise. Identifying the squeal in the noise floor is no problem for our visual system, but for detection algorithms it is a difficult task especially for the lower frequencies. This task is much easier to fulfill when the algorithm performs detection based on psychoacoustic based calculations as shown in the right part of figure 5.

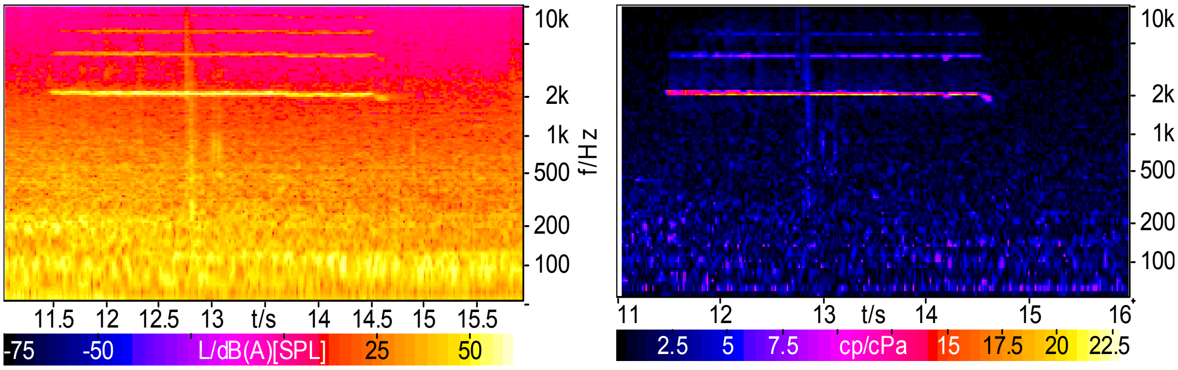

Figure 5: Left: Spectrogram of a cabin microphone recording containing a squeal. The low frequency noise floor is dominated by tire noise. Right: *Relative Approach* analysis vs. time of the same recording. Results of the *Relative Approach* analysis are given in “compressed Pascal” (cPa) since the *Relative Approach* results represent the outcome of the nonlinear and compressing processing of the inner ear. For detection tasks this representation of the recording yields a much better basis than the spectrogram.

6.1.2 Temporal perception threshold for pure tone brake noises

The duration of a brake noise occurrence is an important factor for the annoyance of a squeal. A certain minimal duration is needed before a noise can be perceived as tonal at all. This minimal duration depends on the squeal frequency as results from psychoacoustic experiments show [9]. The squeal detection algorithm should take this dependency into account and should only detect squeals that can be perceived as tonal events. In practice longer minimal durations are required because the human detection capabilities in the driving vehicle are worse than under the lab conditions in the basic psychoacoustic experiments. Own practical experiences with original recordings from driving vehicles led to minimal detection durations in the range from 40 ms to 60 ms for frequencies above 1 kHz.

6.1.3 Detection independent from absolute level

There are some reasons to prefer detection algorithms that are independent of the level of suspicious brake noises: Temporal varying masking effects of ambient noises in the cabin lead to unreliable detections when a fix level threshold is used. The transfer path from the brake positions into the vehicle cabin differs from vehicle to vehicle. In consequence the level thresholds for a level-dependent detection method have to be readjusted for every new vehicle. This process is time consuming and aggravates the comparison of results between different vehicles. In the vehicle cabin the nearly sinusoidal tonal noises may yield to standing waves and hence to level values depending on the position of the microphone. This aspect may be relevant for moan noises in particular. Because of the width of the microphone the probability to measure exactly in a node of the standing wave may be neglected. However, the level may be diminished so far that a reliable detection based on a level threshold is not possible any more. The psychoacoustic-based *Relative Approach* looks for patterns and not for absolute levels and hence avoids the above described difficulties.

6.2 Assessing detection quality

6.2.1 Reasons for wrong detection results

Neither the subjective nor the automated detection of brake noise yields 100% correct results. The subjective identification of the source direction of brake noises is difficult especially for low frequencies. Hence there is a risk to assign brake noises to a wrong brake in the test car and even brake noises from vicinal vehicles are assigned to the own car. Of course also errors originating from concentration problems or caused by unknown hearing impairments are probable especially for squeals near hearing threshold. Other reasons for misdetections originate from other tonalities e. g. singing of birds.

Also the automatic detection may yield wrong results. Since squeals and moans are detected based on their tonality detection algorithms may misinterpret other tonal events not originating from the brakes as brake events. Last but not least problems with defect measuring setups can cause wrong results.

In consequence there is a need to assess the quality and reliability of the detection results.

6.2.2 Sensitivity and specificity

The quality of the squeal and moan detection can be expressed in detection rates and error rates. In order to assess and compare detection rates of different algorithms the expression “sensitivity” and “specificity” may be used in analogy to the medical statistical notation. The **sensitivity** of a method is defined as the number of the squeals **correctly** detected by the system related to the total number of really existing tonal brake noises. The sensitivity characterizes how completely a method discovers the attribute investigated. The total number of really existing tonal brake noises should be determined by jury tests based on artificial head recordings and by analyses of all audio channels. The members of the jury have to be proofed to be normal hearing and must be familiar with typical brake noises.

On the other hand an algorithm may detect brake noises erroneously in recordings that in reality do not contain brake noises. The number of recordings, in which the algorithm **correctly** did not found brake noises, related to the number of the recordings that really do not contain tonal brake noises yields the corresponding **specificity**. The specificity depicts how far exclusive the investigated attribute is found.

Of course high sensitivity and high specificity values are desirable; however for non-trivial tasks often these values stand in a contrary relation. The designer of a detection algorithm has to find a good compromise between both targets.

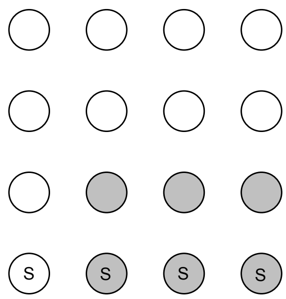

Figure 6: Results of detection system A. Brake events are represented by circles. Empty circles stand for brake events without squeals. Circles marked with “S” represent noisy brake events. The detection algorithm detects those events symbolized by filled circles.

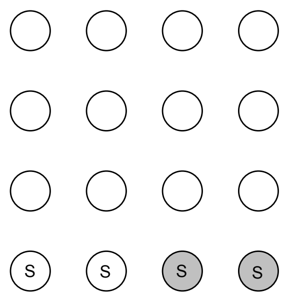

Figure 7: Detection results of system B assuming data from the same test drive as in Figure 6.

As an example 16 recordings were stored during a test session. Jury tests and signal analysis yielded that 4 of these recordings contain squeals. Detection system A found 6 noisy recordings (see Figure 6). Since only 3 of the found recordings contain squeals the detection sensitivity and specificity are:

$$\text{Sensitivity} = (6 - 3) / 4 = 75\% \quad (1)$$

$$\text{Specificity} = (10 - 1) / 12 = 75\% \quad (2)$$

Another detection system B finds 2 noisy recordings for the same spot check. Both recordings were proofed to be noisy (see Figure 7). Thus the detection sensitivity and specificity now are:

$$\text{Sensitivity} = (2 - 0) / 4 = 50\% \quad (3)$$

$$\text{Specificity} = (14 - 2) / 12 = 100\% \quad (4)$$

If one system has higher sensitivity and higher specificity values than the other then it is dominantly better than the other. For the systems A and B in the example this dominance is not given. Which of these systems is preferable depends on the specific task.

7 SUMMARY

In this paper typical brake noises and their causes are presented. It is shown how these hardly reproducible noise events can be evaluated in extensive test drives using special data acquisition systems. The psychoacoustic basis of the automatic detection process is introduced as well as known detection problems and their assessment. The presented methods and equipment may also be suitable for similar tasks where annoying tonalities with small probability shall be assessed with respect to various ambient parameters.

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