Assessment of Harshness Caused by Rattling Car Interiors

AUTHORS

Dr. Stefan Irrgang
is Engineering Manager of the QC Product Line at Klippel GmbH in Dresden (Germany).

Prof. Dr. Wolfgang Klippel
is President of Klippel GmbH in Dresden (Germany).

An innovative test method detects rattling symptoms excited by installed audio systems. The unique combination of objective and subjective criteria to derive meaningful limits ensures the reliable detection of relevant problems only. Flexible implementations and data flow make this method applicable to existing and new test set-ups.

MOTIVATION

Rattling noise generated by the parasitic vibration of panels, doors, dashboards and other mechanical elements in the interior of a car is extremely annoying, especially in new cars. These vibrations are typically excited by common mechanical sources (e.g. the engine) but also by the car's loudspeakers. While engine-induced or braking-induced noise, vibration and harshness (NVH) may indicate an important safety malfunction in a car, there is no useful aspect of interior rattling noise. It is easily detected by occupants and diminishes not only the audio performance but also the driving experience and the reputation of the car manufacturer. Even a 100 % pre-test on a component level [1] is not sufficient, since the car interior is assembled at the end of the production line and is a property of the entire car.

Therefore, a method is proposed to reliably detect such symptoms that are excited by loudspeakers and to provide valuable and reproducible data for the redesign and mitigation of vehicle defects [2].

ROBUST RATTLING DETECTION

There are no standardised terms for the symptoms discussed. In this case, "rattling" is used to describe a group of undesired symptoms such as buzzing, squeaking, rattling or stick-slip noise, all of which are caused by parasitic vibration. The increasing number of loudspeakers in modern cars induces increasing mechanical energy into the car body, especially at low frequencies [3]. This allows the audio system to be a convenient vibration source for detecting rattling. Tests can easily be performed not only to detect rattling but also to check the correct functioning of the installed audio / infotainment system itself (connection, pressure level, polarity, damaged speakers and mounting problems) [4].

Symptoms of rattling are typically high-frequency components generated by low-frequency excitation, **FIGURE 1**a, which are easily detectable by the human ear due to the separation into frequency domains (symptoms are not masked by the stimulus) and the high sensitivity of the human ear in the range from 1 to 10 kHz. A sinusoidal signal is the most critical stimulus for minimising masking effects. A continuous sine sweep, in which the frequency varies with time, excites all potential parasitic resonators. A single, sensitive test microphone is used to record the symptoms in the car. Based on time frequency analysis, the stimulus and the harmonics as well as the defect symptoms can be plotted, **FIGURE 1**b. Using a tracking high-pass filter, the defect symptoms can be isolated and the peak value of the filtered signal in the time domain is plotted together with the frequency response, **FIGURE 1**c. Although the symptoms of rattling are very small in amplitude (-80 dB below the fundamental!), they can be reliably detected with outstanding sensitivity [1].

The test set-up and processing can be efficiently implemented on a PC with a microphone connected. Measurement time is typically below one second for one complete sweep (20 Hz to 20 kHz). When rattling detection is combined with a speaker test, channels or speaker groups (e.g. Left / Right + Rear / Front) can be tested individually, resulting in an overall testing time of only a few seconds.

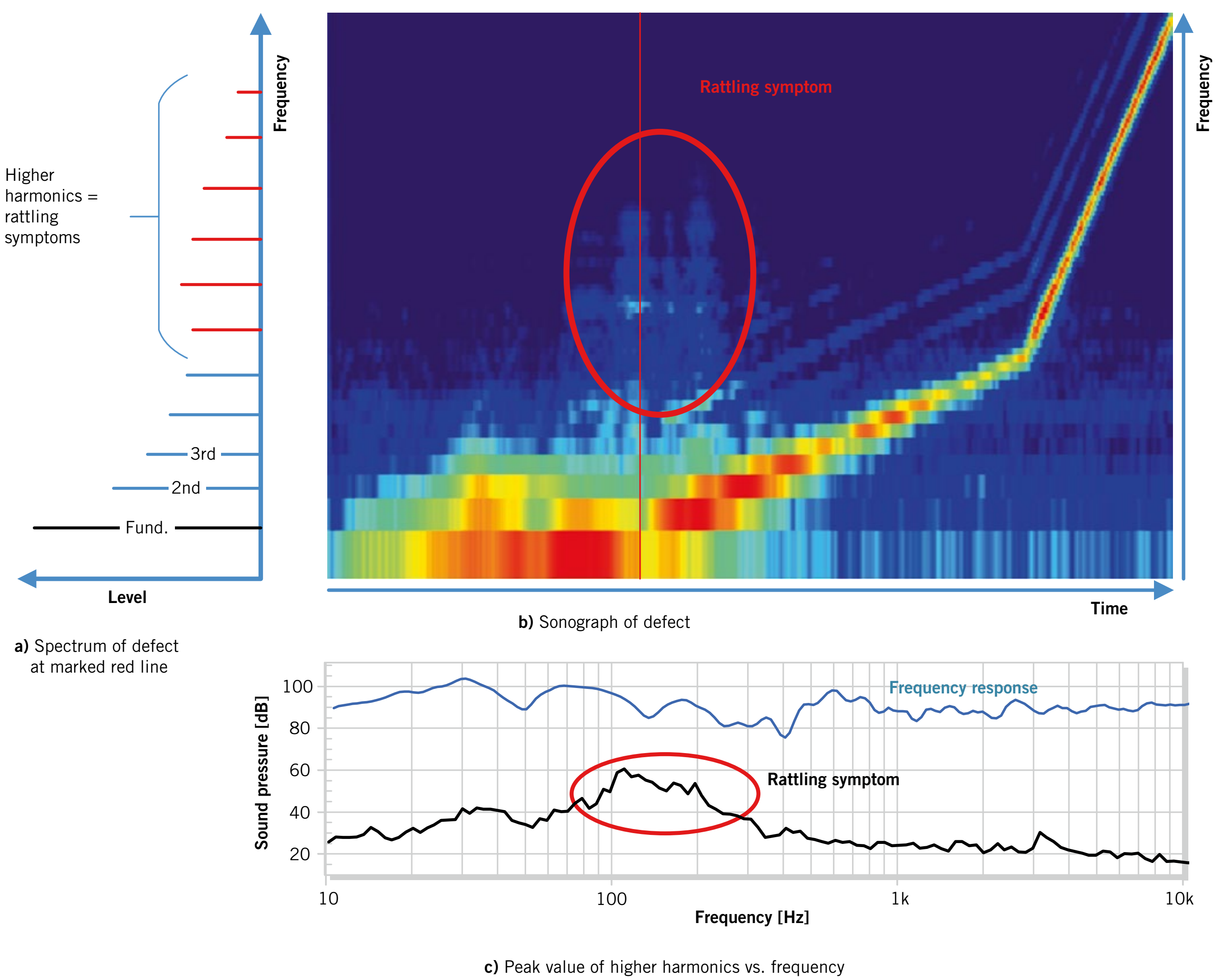

FIGURE 1 Rattling symptom analysis for sine tone (a) and sine sweeps (b, c) (© Klippel)

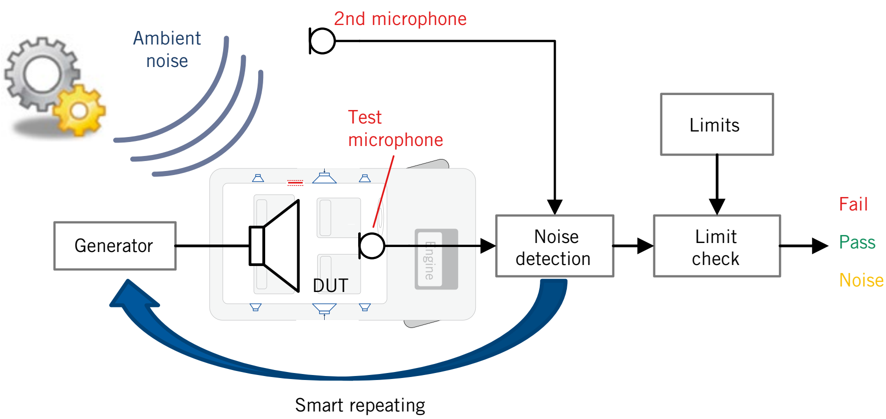

FIGURE 2 A second, exterior microphone detects and copes with ambient noise corruption (© Klippel)

Limits can be defined (see also below) and compared with measurements, thus resulting in a Boolean hard verdict of Pass or Fail.

In a real-world test environment (service, diagnostics station, production line), the detection of low-level rattling symptoms can be easily corrupted by ambient noise that is not produced by the car's audio system. Because of the high-frequency nature of rattling and the unknown source location of ambient noise outside the car, it is not possible to separate and remove them. Additionally, the noise attenuation of the car body (although up to 30 to 40 dB SPL above 1 kHz) is not sufficient to avoid corruption by impulsive ambient noise, which is typically impulsive and can easily be above 100 dBA SPL. For comparison, rattling symptoms may be as low as 30 dBA SPL.

A simple solution is to use a second "noise" microphone outside the car, thus applying identical processing to both microphone channels and accounting for the noise attenuation of the cabin walls, **FIGURE 2**. By using this method, the external ambient noise level reaching the "test" microphone inside the car can be predicted. If both the ambient noise microphone and the test microphone violate the limit at similar frequencies, a third verdict representing ambient "Noise" corruption is returned. In this case, the test is automatically and quickly repeated. As the measurement time is so short, this does not significantly affect the speed of the production line. A smart repetition algorithm can further improve upon speed and accuracy by merging valid parts of each test automatically while discarding parts that are noise-corrupted. Thus, as one frequency range is tested ok, it is marked as valid and a minimal number of sweeps are required until all frequencies are tested without corruption.

ROOT CAUSE ANALYSIS

Rattling defects caused by parasitic vibration of the interior (e.g. loose panels) are hard to locate. Even for a trained operator, it is easier to touch panels and stop the related vibration than to rely purely on acoustic localisation. However, finding the source is the key for easy repair and improvements.

Classical solutions for NVH problems, such as Transfer Path Analysis or Modal Analysis, are not appropriate for non-systematic, sporadic defects. An efficient interactive tool is a sine generator with a microphone probe and the application of the same processing as described above. The closer the probe is moved to the source (similar to a stethoscope), the more easily the symptoms are recognised. A real-time analysis with feedback to a mobile display or headphones (with ear protection for the operator inside the car) is useful and is a fast diagnostics tool [5]. An additional down-sampling of the isolated defect symptom makes the fine structure of defects audible and is helpful in separating them.

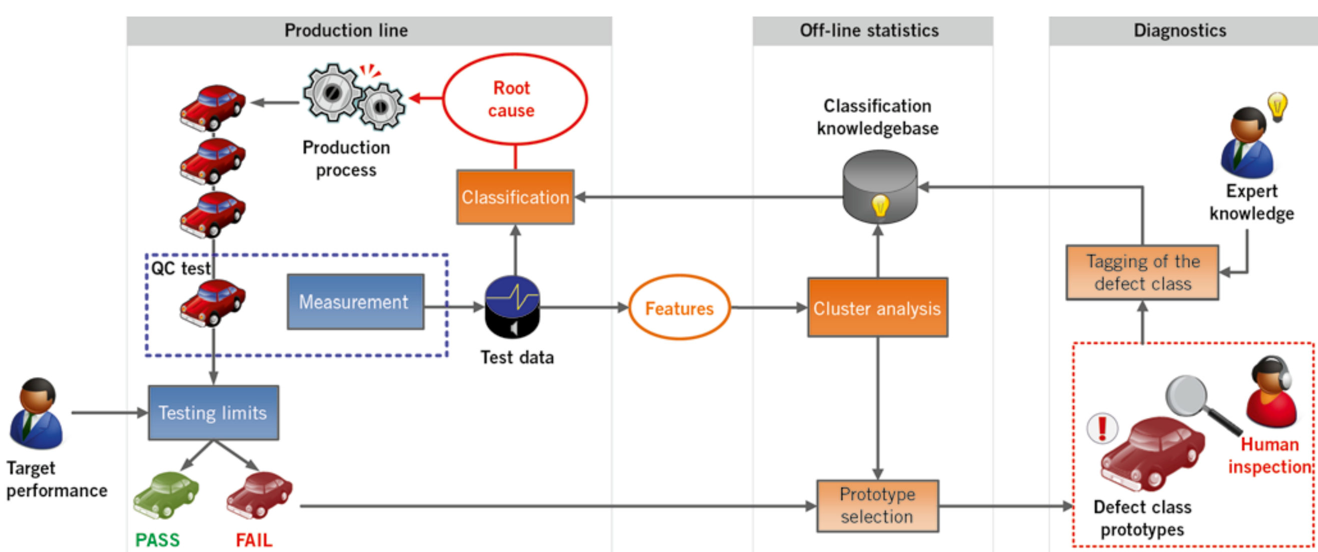

FIGURE 3 Automatic Defect Classification (ADC) used for cars (© Klippel)

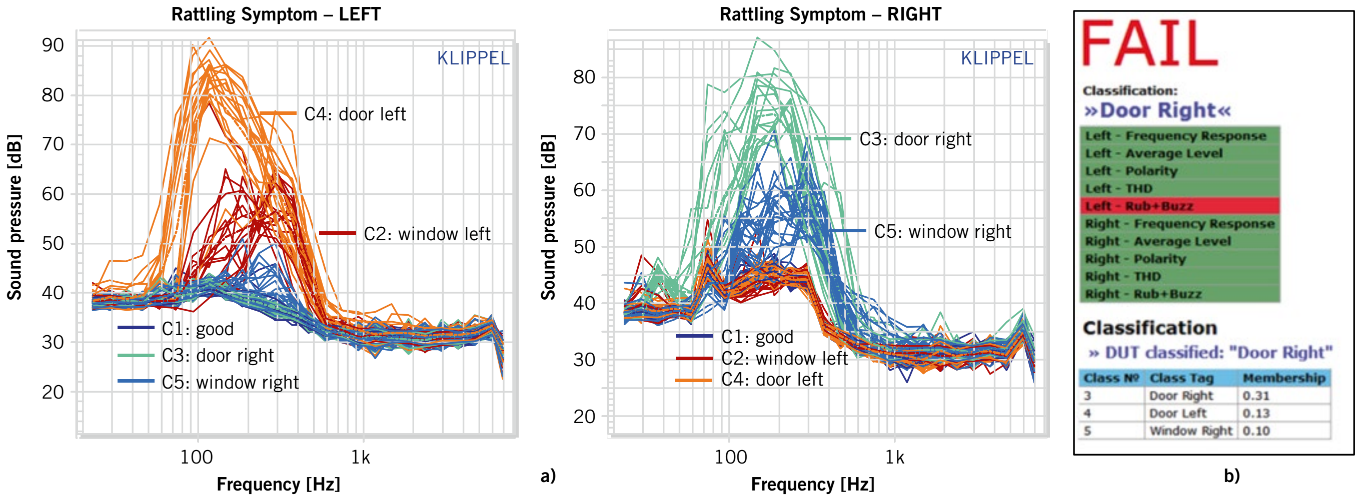

FIGURE 4 a) Rattling symptom "pattern" for the left and right channel b) Fail verdict with classification of the right door defect (© Klippel)

While this interactive troubleshooting is good for detailed diagnostics, it is not applicable for instant repair at the end of the production line due to a lack of time. In this case, a second method based on a statistical analysis of already measured defects is suggested:

On a production line, highly similar objects are compared and extensive result data are available. Cluster analysis is applied as a data mining method and allows the automatic detection of defect classes in such a way that

– members within one class are as similar as possible (probably caused by the same defect) and
– classes are as different as possible (defect separation).

In the multi-dimensional space spanned by measurement properties (e.g. rattling level at a certain frequency), classes are represented by a centre point and a (hyper-) volume. Prototypes for each defect class are those measured samples that are closest to the centre point. They can be automatically identified by the clustering process, analysed by an engineer and finally tagged with a label describing the defect and mitigation options, **FIGURE 3**. This information is stored in a knowledge database and is used for the classification of newly measured defective devices under test (DUT) [6]. In addition to a "hard" verdict, the automatic defect classification system supplements "soft" root causes with their respective membership to known defects. The resulting knowledge database also reveals valuable defect class characteristics, e.g. the most significant property for a certain defect, and can be maintained over time. It can be adaptively adjusted to new defects that were not present before, or no longer existing classes (solved problems) can be deleted.

Using this classification technique, the operator is provided with immediate information about the most likely root cause with a percentage number of how good the current DUT fits to known defect classes. Thus, simple problems can be fixed without moving the car from the production line.

A simple example illustrates this process. For a given car type, rattling defects were found on both the front door panels and on a cover panel above the front door windows. Those four defects are labelled Window Left, Window Right, Door Left and Door Right. **FIGURE 4**a shows the statistical characteristics of rattling symptoms recorded with two (Left and Right) sweeps. The defects are excited only when the respective side was tested. Note the different mean (thick dash-dot) curves and standard deviation (thick dotted) from those defects and the actual measured defects (thin lines). In **FIGURE 4**b, the test result of a measured DUT shows the overall verdict (FAIL), as well as individual verdicts and the most likely root cause (Door Right).

MEANINGFUL LIMITS

Well-defined limits are required in order to separate only those rattling defects which are non-acceptable from normal production variances. The challenge here is to achieve the optimum balance between minimal rattling symptoms and high production yield. Clearly, this depends on the car type, cost and manufacturer. A simple solution is to add a certain amount of headroom to the measured rattling symptoms of a non-rattling car (for example 10 dB, and this may also be frequency-dependent). However, although the assessment of harshness caused by rattling is an objective measurement and the level of rattling symptoms correlate with its intensity, the acceptance of certain defects might be subjective and is usually beyond the responsibility of a test engineer. Consequently, a solution is needed to link objective tests (engineering) and a subjective rating (mainly by management).

The suggested approach is twofold. The measurement explained above is used to find perceptible rattling symptoms. If any symptom is found (a low headroom of 6 dB can be used to indicate this), a critical and approved audio signal with a length of a few seconds is recorded in the car in addition to the measurement. These recordings can then be evaluated by systematic listening tests and the annoyance can be assessed. In a next processing step, the undesired defect symptoms d_{dis} can be separated from the desired (reference, accepted or good) signal x_{ref} and scaled with a user-definable gain. This method based on subtraction in the time domain is called Difference Auralization and is

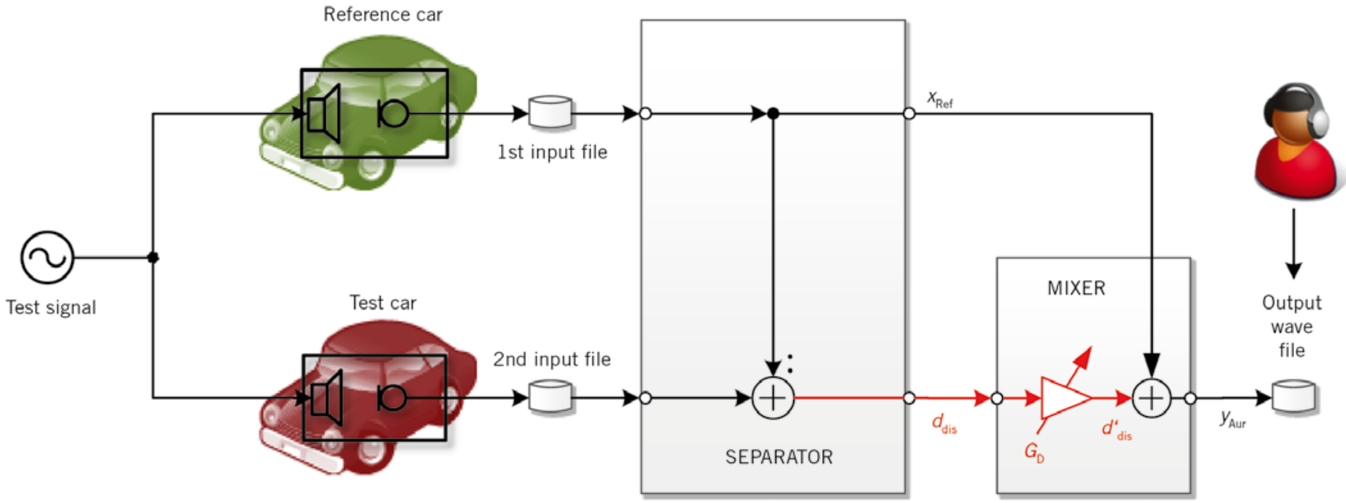

FIGURE 5 Difference Auralization for the subjective evaluation of rattling symptoms (© Klippel)

illustrated in **FIGURE 5** [7]. The output y_{AUR} of this method is the reference signal added with a scaled (attenuated or amplified) amount of rattling (defect) symptom d_{dis}.

The subjective listening test can be supplemented with an analysis of objective perceptual measures (sharpness, roughness, distortion to mask ratio).

The gain control GD can now be adjusted in such a way that the resulting output signal is just acceptable. An automatic double blind test method is recommended and can be evaluated at www.klippel.de [8]. Based on the GD value found, the headroom of the objective measurement of the rattling symptom can be adjusted. The result is a meaningful limit based on subjective and objective evaluation. It is also an efficient method for getting decision-makers involved in the limit definition process, since those limits are usually related to cost, time and yield. The suggestion is to define limits in pre-production phases to ensure reliable limits during full production. However, limits can also be adjusted adaptively during production, but they should be carefully logged. **FIGURE 6** illustrates the workflow on the limit calculation process.

It is recommended to collect as many data sets as possible before defining limits using the above-mentioned method in order to have a statistically relevant number of defects (which is usually still small) for the automatic defect classification and listening tests. It is also reasonable to store all responses from cars with perceptible symptoms for re-calculating verdicts when limits are adjusted. Thus, the change in the yield can be predicted by an analysis of cars already measured.

PRACTICAL ASPECTS

In this section, implementation details and options are discussed. The method presented can be used not only for the production line but also for R&D, lifetime checks and repair shops.

Reproducible results require a well-defined microphone position. Tolerances of a few centimetres are no problem, since no absolute phase information is used. For normal cars, one microphone is sufficient. A good microphone position is in the centre of the car (between the headrests of front seats). For large cars or for extreme sensitivity, more microphones can be used. The SNR of voice recognition microphones installed in a car is usually not sufficient and, what is more, microphones are not standard equipment in all cars. The position of the ambient noise microphone outside the car is not critical and a distance of 1 to 3 m is good. Moving production lines can even use a distributed microphone system along its length.

Processing can be performed on a standard PC, and even one that is already being used for other QC checks. A laptop or mini-PC inside the car can also be used, but no person must be in the car during the test. The test microphone should be connected to an audio interface using a cable or an uncompressed wireless transmission (≥ 20 bits) whereas the noise microphone is not as demanding (16 bits). A wired microphone system is not acceptable for higher volume testing.

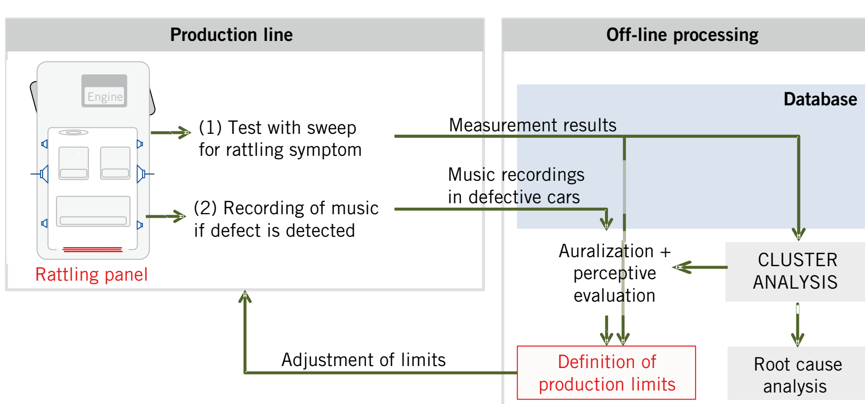

FIGURE 6 Objective and subjective criteria used for limit calculation (© Klippel)

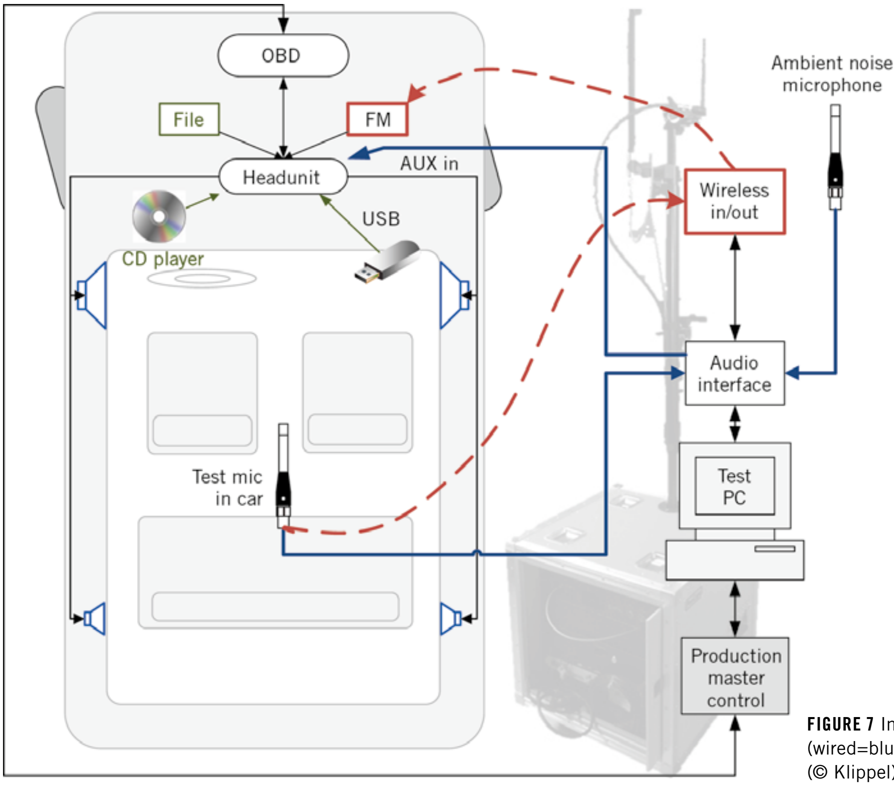

FIGURE 7 Input and output options for rattling detection in cars (wired=blue, wireless=red, a-synchronous stimulus=green) (© Klippel)

Several options are available for the test stimulus. It can be generated by the PC on the fly and transmitted by cable or wireless (FM, Bluetooth, MOST) or can be stored as a wave file in the head unit or on a CD / USB stick. The latter case requires a trigger to start the test signal and automatic synchronisation of the analyser to the captured test signal. In intelligent cars, this can be fully controlled by test apps that might also check closed windows and doors as well as controlling individual speaker channels for multiple tests. In more conventional cars, the test PC can perform control using OBD or other bus systems. The average test level inside the car needs to be manually adjusted or can be dynamically adjusted by an initial level set-up step.

All data analysis can also be carried out on a (remote) server. The responses to sweep and music samples can be captured and sent to a processing PC or server via the internet or intranet. Thus, the equipment on site (repair shop) is minimal. All that is required is a standard audio interface, a test and a noise microphone (noise mic optional) and network access for downloading the stimulus and uploading the responses.

For production lines on which different car types or models are produced, individual set-ups and/or limits can be loaded depending on the vehicle ID number or similar information.

SUMMARY

Harshness symptoms caused by parasitic vibration of the interior are very annoying, but they are also easy for occupants to detect. A test method is presented for the reliable detection of rattling symptoms excited by the installed audio system for the purposes of development, production quality checking and shop service. The unique combination of objective and subjective criteria to derive meaningful limits ensures the reliable detection of relevant problems only. Automatic root cause analysis provides quick diagnostics and repair instructions, exploiting problems from the past. The required testing time of a few seconds includes a comprehensive check of rattling symptoms and other essential tests for the audio system. Flexible implementations and data flow make this method applicable to existing and new test set-ups.

REFERENCES

[1] W. Klippel: End-Of-Line Testing. Assembling Line, Theory and Practice. Chapter 10, INTECH 2011
[2] S. Irrgang, W. Klippel: In-Situ Detection of Defects in Car Audio Systems. 48th International Conference of the Audio Engineering Society, Automotive Audio, 2012
[3] R. Shively, J. King: Automotive Doors as Loudspeaker Enclosures. 114th Convention of the Audio Engineering Society, 2003
[4] K. Ritter: Detektion von parasitären Schwingungen und Störgeräuschen im Automobil. Diploma Thesis, Dresden University of Technology, Institute of Acoustics and Speech Communication, 2011
[5] W. Klippel: Anordnung und Verfahren zur Erkennung, Ortung und Klassifikation von Defekten. German patent application DE 10 2009 033 614
[6] T. Burstika: Automatische Klassifikation von Lautsprecherdefekten. Diploma Thesis, Dresden University of Technology, Institute of Acoustics and Speech Communication, 2012
[7] M. Liebig: Subjektive und objektive Bewertung der Klangqualität im Automobil. Master Thesis, Dresden University of Applied Sciences, Institute of Electrical Engineering, 2012
[8] Interactive Listening Test using Auralization of Signal Distortion, http://www.klippel.de/listeningtest/lt/

DOWNLOADING THE ARTICLE
www.springerprofessional.de/ATZextra