# In-situ Detection of Defects in Car Audio Systems

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## ABSTRACT

Checking the sound quality of a car audio system at the end of the production line is required to satisfy rising customer expectations. Although transducers are pre-tested defects may be caused by improper handling during mounting. Those defects such as loose panels have a high impact on sound quality, are clearly audible but difficult to detect. A method is presented combining highly sensitive defect detection, root cause analysis for failed tests and assistance for meaningful limit definition.

## 1. INTRODUCTION

The sound quality of a car audio system is typically defined by the R&D department and is verified during various prototype phases. This comprises modern simulation techniques and measurements in the vehicle.
The Quality Control department ensures the defined audio quality within specified limits during prototyping, pre-production and full production in accordance to specified target performance.

The distortion generated by the audio reproduction system can be split into signal components as shown in Fig. 1 [1].

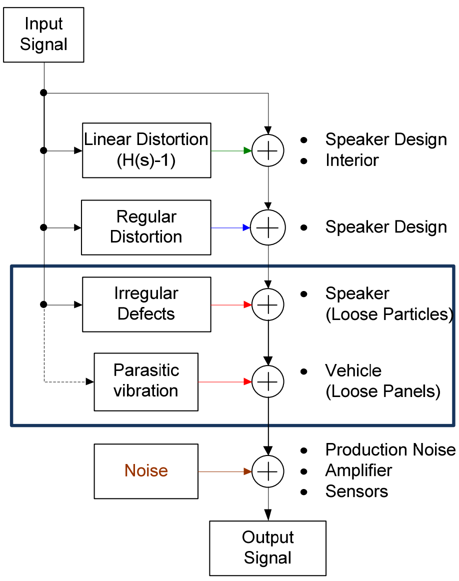


Fig. 1. Distortion decomposition in a vehicle

Linear and Regular distortions are defined by speaker design, the acoustic properties of the car interior and the tuning of the equalizers and other signal processing. The frequency response, sensitivity, harmonic and intermodulation distortion as well as spatial characteristics are less critical in car manufacturing because the loudspeaker drive units and electronic components are tested by the supplier.

Even if those characteristics are varying beyond defined limits, it is rather difficult for the end customer to rate the quality as bad and consequently making a complaint.
This is quite different for excessive distortion generated by

- defects (e.g. „rub and buzz“) of the sound reproduction system (transducer and loudspeaker enclosure [2], mounting, amplifier, cables, connections) and
- parasitic vibration (buzzing) caused by improper mounting of interior car components (loose parts, grill, windows, panels, ... ).

Those defects are easy detectable by customers because the impulsive properties of the irregular distortions are perceived as unnatural and annoying.

Those defects produce two kinds of consequences for the car manufacturer:

1. Hard cost: Defined by exchange of defective parts and / or repair in a remote garage. Additional costs arise from investigation and tracking of the defect by the manufacturer. Cost calculation is rather simple.
2. Soft cost: The reputation of the brand will suffer from those defects although faint defects may be tolerated by the end-customer. This cost is very difficult to estimate.

Traditional measurement techniques applied to production monitoring check the connectivity to speakers and the basic acoustical performance, such as average level, polarity and regular distortion only. Also subjective methods are applied to assess the audio quality e.g. during a test road run, in most cases on a sampled base only.
In this paper a method is suggested to monitor the above mentioned objective criteria and the excessive distortion with the following main objectives:

- 100% end-of-line testing and PASS/FAIL classification of each device under test (DUT)
- Root-cause analysis to detect defective audio components (speaker, amplifier, cables, connectors) and manufacturing problems (loose panels, damages of speaker, missing screws)
- Objective assessment of sound quality
- Ultra-short and reliable measurements under noisy production environment
- Integration into existing infotainment test
- Easy handling and interpretation of results, diagnostics
- Modern data management, traceability, documentation
- Process statistics and control

Aging of speakers is not considered, this method is strictly focused on car manufacturing. It is furthermore assumed (but not required to apply the suggested methods), that the speaker are fully tested by the speaker supplier (OEM). Defects may primarily caused by

- transportation and storage of the transducer
- handling (damage speaker cone)
- mounting (loose screw, loose panel)
- systematic deviation (within spec) in driver manufacturing (change of material, supplier)

Those potential defects are under the responsibility of the car manufacturer.

## 2. DIAGNOSTICS OF IRREGULAR DISTORTION

This paper focuses on irregular defects of the mounted speakers and on parasitic vibrations.

### 2.1. Electrical Diagnostics

Diagnostics software directly implemented in the head unit can monitor the connection and correct type of mounted speaker. Advanced methods are capable of checking also the nonlinear properties (Regular Nonlinearities, e.g. voice coil position, stiffness characteristics) [3][4]. Electrical tests are based on impedance monitoring, which reflects the back-induced voltage from the mechanical motion. Faint defects (e.g. loose particles or litz wire beat) are well audible, see below. However, they do not produce a detectable motional change of the voice coil. Hence they cannot be monitored using impedance test.

Parasitic vibrations are even more remote and do not cause measurable feedback via an acoustical transfer path to the coil. This poor feedback on the other hand is the reason for the implicit noise immunity of electrical tests.

Consequently electrical tests are needed but are not sufficient to validate an expected sound quality in vehicles.

### 2.2. Acoustical Diagnostics

Both, irregular defects of the transducer and parasitic vibration of the panels produce impulsive distortion in the sound pressure signal which can be easily detected by using a sinusoidal stimulus (e.g. sweep) as stimulus and a microphone [5][6].

Whereas regular distortions are dominant at low harmonic orders (e.g. up to 10), irregular distortions of defects are typically dominant at higher frequencies (Fig. 1, Fig. 2). A simple high-pass may be used to attenuate the fundamental and the regular distortion. Although, irregular distortions are very small in amplitudes (80 dB below fundamental). They are well audible for the human ear due to the greater spectral distance to the excitation tone. Irregular distortions comprise both harmonic components corresponding to deterministic causes and non-harmonic components at other frequencies corresponding to random defects (loose particles and air leakage noise [7]). Based on empirical tests using different cars and transducers, a high-pass order of 10 was used.

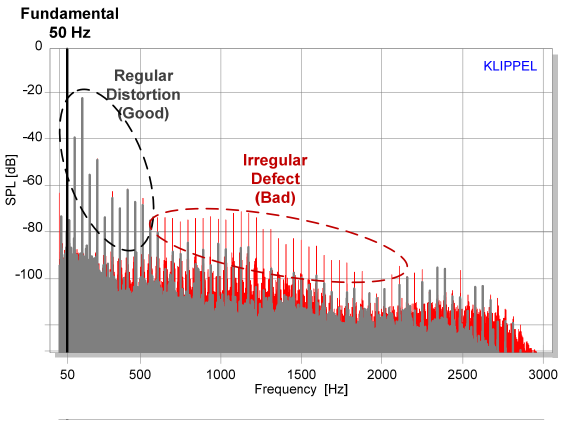


Fig. 2. Distortion components vs. frequency of a fixed sine tone (Note the linear X-axis)

To detect a defect at high sensitivity and to cope with measurement noise all available symptoms have to be collected by an optimal signal analysis. The amplitude of the high-frequency components reveals only the energy but not the impulsive nature of the irregular distortion. Transforming the complex spectrum of the high-pass filtered signal with sufficient bandwidth back into the time domain reveals characteristic transient distortions having a low rms value but a relatively high peak value. The high crest factor (C >12 dB) is a unique feature of irregular distortion and correlates with the phase information of the distortion spectrum. The peak value is determined at sufficient temporal resolution and assigned to the exciting frequency of the stimulus [1]. It is a very sensitive “Rub&Buzz” measure. PASS/FAIL limits can simply applied as shown in Fig. 3.

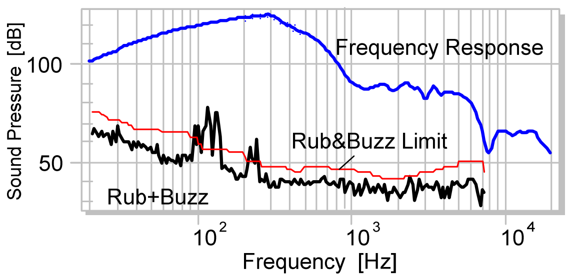


Fig. 3. Typical peak value of irregular distortion (labeled as Rub&Buzz) vs. frequency of a defective audio system

A drawback of the acoustical test is the vulnerability to any other noise source such as production noise.

## 3. TESTING IN PRODUCTION ENVIRONMENT

Loudspeaker measurement during research and development in a lab environment and end-of-line testing in transducer manufacturing is state of the art. In a typical vehicle production facility a measurement system must cope with additional challenges:

- Minimal test time
- Production Noise Immunity.
- Integration into Production / Infotainment test process
- Simplicity of operation

### 3.1. Test Time Considerations

High speed measurement cannot be accomplished by using a stepped sine wave as stimulus and performing a steady-state measurement at selected frequencies. Testing an audio system at full bandwidth from 20Hz to 20 kHz in less than 1s this stimulus provides only a low number of frequencies which cannot excite narrow band resonances with high Q factors as found in parasitic vibrations and most loudspeaker defects.

Ultra-fast measurements require a transient measurement technique using a continuous sweep or chirp signal which excites all frequencies. The time-frequency mapping of the sinusoidal sweep is important for optimal sensitivity. Logarithmic sweeps are commonly used but are not optimal for exciting loudspeaker defects and other mechanical resonances which require a slower sweep speed at low frequencies and a higher sweep speed at high frequencies.

A sweep with varying speed profile provides the best excitation conditions and maximal resolution in distortion analysis for a given total measurement time [8]. This technique makes it possible to detect defects reliably with an extremely short test time of 0.2-1s.

### 3.2. Production Noise Immunity

In a vehicle production plant or even at diagnostics stations in a typical garage ambient noise does interfere with defect detection of low energy symptoms. Typical production noise consists of two parts:

- Background noise (steady state) at typical level of up to 70-80 dB with pink noise characteristics.
- Instantaneous noise events (short term) with much higher level above 100dB e.g. from dropping parts or squeaking wheels.

The ambient noise generates no problem for the measurement of the fundamental component if the sound pressure level inside the car exceeds 90 dB. However, as mentioned above, the level of defect symptoms may be as low as 60-80 dB below the fundamental. Thus care shall be taken, that symptoms at 40 dB must not corrupted by production noise.

Fortunately, the vehicle body with closed windows provides acoustical damping of the ambient noise (like a test enclosure, which is typically used in transducer production). Fig. 4 shows the ambient noise attenuation measured in 3 cars representing different market segments.

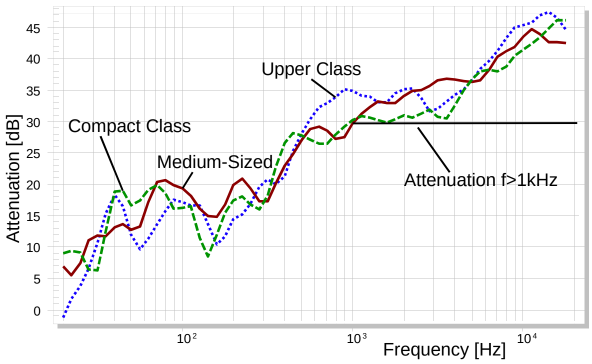


Fig. 4. Typical ambient noise attenuation of 3 different cars (from [9])

All have in common, that above 1 kHz at least 30 dB damping can be expected which attenuates the background noise (steady state) to 40-50 dB inside the cabin.

For instantaneous noise events (short term) the damping of the cabin is NOT sufficient and the noise level inside the cabin would corrupt the measurement and produce false rejects in the defect detection.

Invalid measurement corrupted by ambient noise can reliably be detected by using a second microphone outside the car (Fig. 5) and predicting the noise inside the car by considering the noise attenuation of the cabin [8]. A sophisticated algorithm [9] can cope with instantaneous noise events (short term) by repeating the measurement automatically and splicing the valid parts of corrupted measurements together until the test is complete. However, the verdict FAILED can be generated at any time and no further testing is required if the measured curve exceed the permissible limit at a frequency where the predicted noise level in the cabin is far below the symptom of the defect.

The ambient noise detection combined with smart repetitions of ultra-fast measurements using sweeps with speed profile produces valid data at full noise immunity within minimal time.

Active cancellation or other forms of compensation for ambient noise in the measured signal is not possible using only a few microphones due to complexity of the 3D sound field and missing information about the location of fixed and moving sources.

### 3.3. Integration into Production Process

The total acoustical test applied to a vehicle comprises a sequence of atomic tests to check all transducers inside the vehicle. Each atomic test provides

- routing the electronic audio system
- exciting one or more loudspeakers by the stimulus
- recording the response and evaluating defect symptoms
- applying noise immunity check (may need repetitions)
- verdicts by comparing with pre-defined limits
- PASS/FAIL classification.

The test microphone shall be placed at optimal position (e.g. rear mirror) inside the car to measure acoustical symptoms of the defects at a good signal to noise ratio [9]. Both the test signal and the ambient noise microphone are transmitted to a test PC where the digital signal processing is performed. Due to the closed cabin a wire-less transmission of one channel may be required. The stimulus can be provided to the car audio system by the following options:

1. The Test-PC generates and supplies the stimulus via AUX IN or USB connection to the head unit.
2. The stimulus is stored and played back from memory inside the head unit
   a) triggered from the test PC.
   b) played back in a continues loop.
3. The stimulus is stored on CD or USB media and played back in a continuous loop.

Option 1 and 2a are synchronous tests; the test can be started anytime and no delay has to be considered.
Option 2b and 3 are asynchronous tests. The test gear must be capable of synchronizing the recorded response to the test stimulus.
Additional means may be required to compensate for different sample rates, if multiple independent audio converters are involved (option 2 and 3) [11].

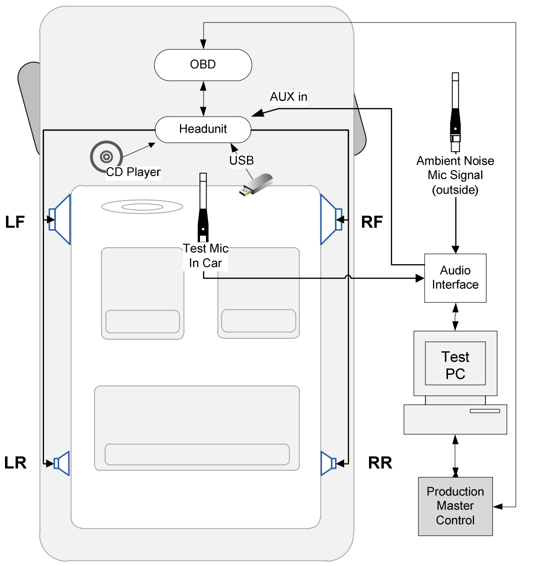


Fig. 5. Test Setup comprising a test-PC with Audio Interface, two microphones and a production master control

The test gear shall be controlled by a superior production system (line automation or master infotainment test). This way the setup (volume, balance etc.) can be set up before calling the test step to be executed as a slave process without operator interaction using the on board diagnostics interface (OBD). The test result is then returned to the calling application and processed accordingly. Other methods of control are also possible.

## 4. ROOT CAUSE ANALYSIS

Finding the root cause of defects is a basic prerequisite for repairing the vehicle at low cost and as fast as possible. This information collected at assembling line is also a valuable feedback for the R&D engineers to increase the robustness of the product and to simplify the manufacturing process.

### 4.1. Audio Channels

A simple and natural approach to root cause analysis is the separate test of the audio channels in a car. Typically four channels are to be tested in vehicles:

- LF: Left-Front
- RF: Right-Front
- LR: Left-Rear
- RR: Right-Rear

Those channels can be easily assessed via OBD using the balance and fading control. No additional control commands are required. For each channel one test step (see chapter 3.3) is to be performed.

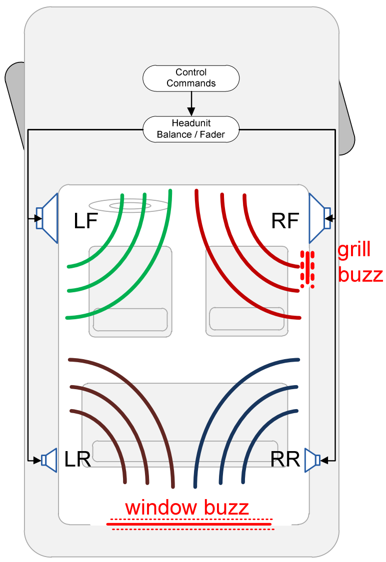

Fig. 6. Individual channel test. Excitation of parasitic vibration via mechanical and acoustical path

### 4.2. Acoustical vs. Mechanical Excitation

Parasitic vibration of the panels and car interior components are excited by either mechanical vibration transferred directly via constructional elements or by the sound pressure inside the car.

- **Mechanically induced**: The mechanical structure of the car body behaves as a perfect transmission path for mechanical vibration from the primary source (engine, tire-road, and loudspeaker) to the parasitic resonator generating the rattling sound. The closer the parasitic resonator to the primary source the higher is the sound pressure level of the distortion. Operating each loudspeaker of the multi-channel audio system as individual primary sources is a convenient basis for localizing the approximate position of the resonator while using a single microphone at a fixed position. For example Fig. 6 shows a grill buzz which can be easily excited by the right front (RF) channel but it is very difficult to activate the defect from remote loudspeaker positions (LF, LR, RR).
- **Acoustically induced**: At low frequencies, where the wavelength is higher than the cabin dimensions, the sound pressure generates a significant force on larger panels such as windows or roof panels that is proportional to its area. It does not matter by which primary source the critical sound pressure is generated. Thus, the window buzz illustrated in Fig. 6 may be activated by any audio channel and produces similar symptoms in all atomic tests of the measurement sequence.

Analyzing the symptoms of excessive irregular distortion of all channels allows the separation of air born and structural born parasitic vibrations.

### 4.3. Simple Defects

It is almost common practice to check each drive unit by the loudspeaker manufacturer for bad magnetization, mass / compliance deviations, wrong polarity and all kinds of irregular distortion (Rub&Buzz) before shipping to the automotive customer. During production relatively simple problems may occur such as

- Transducer not connected
- Wrong Polarity due to cable or assembly problem.

Those defects can be easily detected by checking the SPL fundamental phase and magnitude response using larger tolerances that are coping with the normal variations of acoustical properties related to customer-selected configurations of the particular vehicle.

### 4.4. Rattling, Squeaking, Buzzing Defects

Careless handling of the drive unit during car assembly may cause a damage of the sensitive cone, diaphragm or surround. Improper mounting may result in loose parts, air leaks and other irregular defects causing Rub&Buzz and other impulsive distortion which are difficult to detect and to assign to root causes. The fundamental sound pressure response and the impedance provide no reliable symptoms. Only the peak value of the higher-order distortion (see Rub&Buzz measure in section 2.2) supplies reliable clues depending on car model and audio system and modifications selected by the end-customer. Root cause analysis seems to be interesting only for failed vehicles, violating a defined limit.

A powerful approach for those critical defects is a classification method based on a fuzzy cluster algorithm. This method comprises 3 steps:

<u>1st Step: Off-line Cluster Analysis</u>:
All tested cars are grouped in a number of clusters where each cluster should be as compact as possible and comprising cars with similar properties only. This process uses the results of the measurement (e.g. frequency response data with one third octave resolution) and performs a statistical analysis of those data. The results are the mean values and variances of each cluster which may be interpreted as the center point $P_1$ and the volume $V_1$ of the cluster as illustrated in Fig. 7 [12].

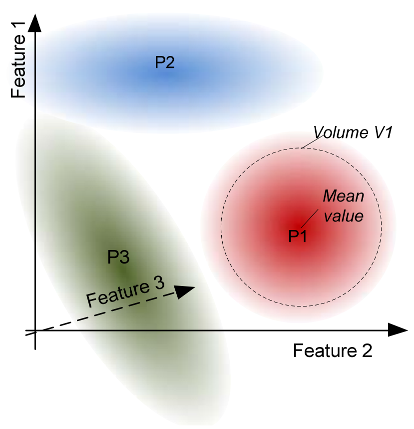


Fig. 7. Clustering of data in a 3 dimensional feature space

2nd Step: Interpretation-Tagging:

Cars which are close to the center point P of the cluster represent a particular defect best. They are used as prototypes and are taken to diagnostic station to perform additional measurements and careful visual inspection to identify the physical cause of the problem. Optional listening to music and test stimuli can be used to assess the subjective perception. The most relevant features (e.g. critical frequencies in the Rub&Buzz response) which distinguish the cluster from other defects are also provided from the cluster analysis. Finally the cluster can be labeled with a specific descriptor, meaningful to other line operators and engineers. The cluster is now upgraded to a defect class, which can be used in on-line classification. Additional information (photos) and parameters of the production process may be collected for each defect in a knowledge data base growing over time.

3rd Step: On-line classification:

The information available in the knowledge base can be used for a defect classification at the assembling line as illustrated in Fig. 8. For each car failing the test a verbal description, fault code and the membership (in percent) to the most likely defect classes are displayed.

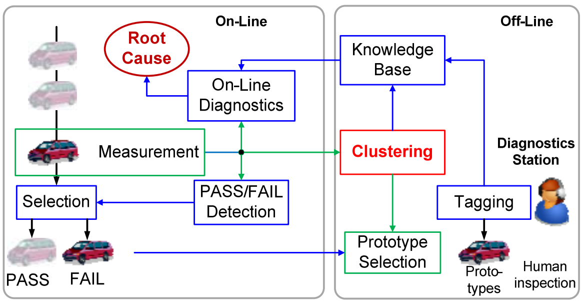


Fig. 8. Overview on root cause analysis

This method was applied to measured data of 79 compact cars at the end of a production line. 4 sub-models (3 door or 5 door car with high level audio system or standard audio system) are made on this line. All of the cars passed the end-of-line test.

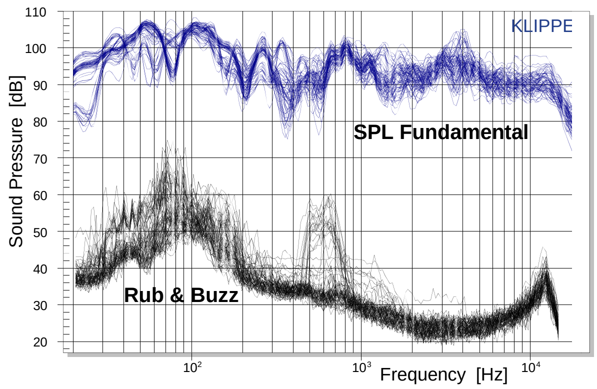


Fig. 9. Measured response of fundamental SPL (top) and Rub&Buzz (bottom curve) of 79 vehicles

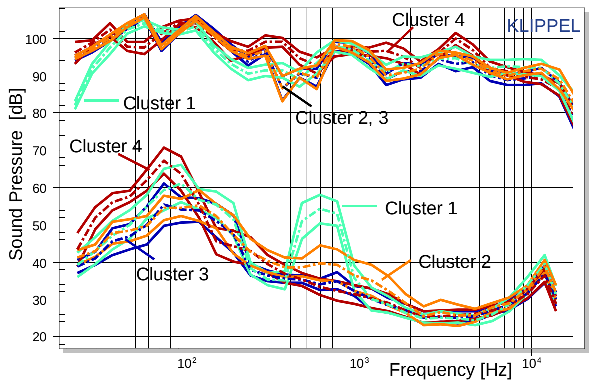


Fig. 10. Test data of Fig. 9 automatically assigned to 4 clusters.

Fig. 9 shows the responses of the SPL fundamental and Rub&Buzz of the 79 cars overlaid in one diagram. It is difficult to interpret the curve and to group the data manually. The cluster algorithm automatically detects the optimal number of classes by assessing the compactness of the clusters by quality measures. In this example 4 clusters separate the measurement data in a most distinct way.

Fig. 10 shows the color coded clusters derived from the original data shown in Fig. 9. The prototypes of each cluster are drawn with a dotted line. The solid lines indicate the range of one standard deviation for each cluster. This graphical representation simplifies the interpretation of the statistical properties:

- Cluster 1 (18 DUTs): comprising all standard system 3-door DUTs with a distinct Rub&Buzz symptom at about 700 Hz.
- Cluster 2 (9 DUTs): Standard system 5-door DUTs with higher Rub&Buzz between 600 and 1500 Hz.
- Cluster 3 (35 DUTs): Similar to Cluster 2, also standard system 5-door DUTs but with lower Rub&Buzz between 600 and 1500 Hz.

- Cluster 4 (17 DUTs): 3+5 door DUTs with high level audio system.

The number and properties of the clusters correspond mainly with the car configurations. In addition the 5-door cars with standard audio system are divided into two clusters, showing higher and lower irregular symptoms (Rub&Buzz). For the cars with high level audio system no distinct difference between 3 and 5 door vehicles was found and hence they are combined in one cluster.

This example shows that the cluster algorithms is a powerful tool for extracting the relevant information (even without any limit consideration) from large amount of data to build up defect classes for critical problems such as buzzing, rattling or squeaking noise.

## 5. MEANINGFUL LIMITS

At the end-of-line a PASS/FAIL decision is made whether quality of a produced vehicle corresponds with the quality standard and can be delivered to the customer.

The definition of permissible sound quality expressed as production limits depends not only on the audibility of the distortion but also on other factors related to the

- Internal or intended public perception of the brand or model
- Failure rate and costs caused by the amendment
- Capabilities for repairing defective units within production cycle or off-line

Consequently, the definition of the production limit is a complex and cost-related decision requiring good communication and a common language between production / engineering and management. The physical results from the measurements, commonly used by engineering, does not describe the audibility of the distortion and the impact on the perceived sound quality which is more interesting to the management.

There is apparently a need to combine physical and perceptive assessment of the sound quality in cars. If a tested car is classified as critical by the measurement system the wave form of the acoustical response is recorded. Additionally an ordinary audio signal (music) is reproduced in the car and the acoustical response is also recorded. Those audio samples should be critical program material [13] which has been approved before usage. Using such recordings, listening tests could be used to distinguish between acceptable and bad sound quality. Based on the related sine sweep responses (objective measurement) limits can be derived, that represent the listening test results (Fig. 11).

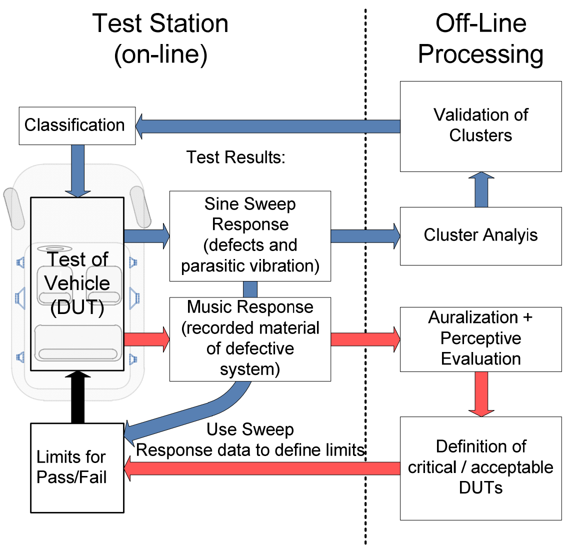


Fig. 11. Limit definition combining objective and subjective test results.

Limits must also consider the capability of the production process. More critical limits will increase the reject rate. Using the classification method, dominant root causes can be identified and resolved in the next revision. Consequently, limits can be adjusted to the increasing quality of the production.

A good correlation of symptoms from sine sweep and music signal responses is assumed. Future research is required for verification. The subjective listening test can be supplemented with an analysis of objective perceptual measures (sharpness, roughness, noise to mask ratio) [14].

## 6. CONCLUSIONS

A comprehensive test method for defect detection in the car production has been introduced. Excessive irregular distortion e.g. from loose panels is reliably detected using an ultra-fast sine sweep excitation. Robustness in a production environment is required. A sophisticated ambient noise immunity technology eliminates the impact of production noise. An electrical test cannot be used to detect such defects.

In case of a failed test a defect classification in the on-line process provides a root cause analysis based on statistical evaluation of preceding tests stored in a knowledge base. This optimized repair time and cost.

The definition of limits is usually a compromise of product, process capabilities, yield rate and cost. For failed or as critical classified objects the responses of test signals and dedicated sound samples are recorded. They are used for evaluating the subjective perception of defects and for defining limits for irregular distortion.

The applied method can be used for 100% on-line production test or on a sample based test station for in-depth diagnostics.

Future research is required on the correlation of subjective and objective evaluation of defects related to particular defects in automotive application.

## 7. ACKNOWLEDGEMENTS

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