Self-Testing of Car Audio System

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All hardware components required for a test system that checks the quality of the audio system in cars are actually already available in modern cars: DSP, converters, sensors, transducers and connecting links. However, they are not designed as test system components but may be used as such. Smart amplifiers and speaker control technologies are of special interest for this approach. They provide powerful means to improve transducer properties like robustness, linearity, and bandwidth. By definition, they identify speaker parameters and states. Such valuable information can be exploited for test and measurement tasks such as design qualification, end-of-line testing, quality assurance, long-term monitoring and ensuring safety relevant features (e.g. pedestrian warning systems). This paper investigates benefits and challenges of this approach.

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 simulation techniques and measurements in the vehicle using test gear (e.g. artificial head, measurement microphones). For objective in-situ testing, usually measurement microphones and external analyzers are used [1][2]. Checking the sound quality at the end of the production line is mandatory to satisfy rising customer expectations and to ensure consistent, high audio quality in delivered cars. A 100% component pre-test is not sufficient, since many defects may easily be caused by improper mounting or connection of speakers or interior panels. Many cars manufacture still rely on subjective or sample-based tests and avoid 100% testing. Reasons for this are the required test time, the complexity of the test setup, requirements on test conditions (closed windows, low background noise), manual operation – hence the overall cost is high. In most cases the audio system is not tested anymore once the car left the factory.

To overcome those obstacles, a self-testing procedure without manual interaction and external test gear would help considerably. Although all required hardware components for measurements in a car are already available (even if they are compromised in performance), the analysing software and framework is not available yet. Porting test and measurement software to the embedded system (e.g. the head unit) is possible [3], but the effort is quite high.

A new approach is using speaker control technology, which by itself is a full monitoring test system for speakers. Assuming the speakers in a car are equipped with speaker control methods, the required additional cost is very low. No external equipment (mic, amp, stimulus, routing) is required, and the setup is identical to the end user configuration. For a fully automatic process (no operator required), a minor software part is required that triggers the self-test and derives warnings or errors and stores results.

In chapter 2 a short overview on speaker control is given while in chapter 3 the useful results for testing purposes are discussed. Since speaker control is currently restricted to the electric domain, additional sensors can extend this method to a more comprehensive test system (chapter 4). This paper closes with a brief discussion of typical test applications in the car life cycle and how testing can be expanded to the actual usage of cars in the field, where until today no test has been established.

2 Loudspeaker On-line Monitoring

A typical car audio setup (Figure 1) comprises sound sources, DSP, amplifier, speaker and also microphones (hands-free, ANC).

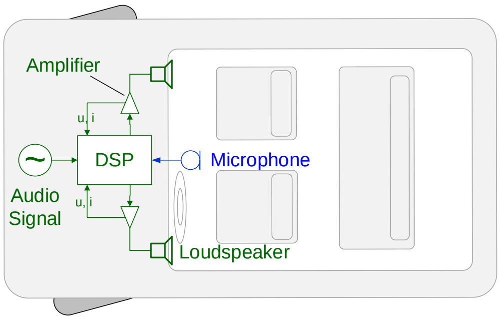

Figure 1: Audio setup in a car

2.1 Nonlinear Control

Loudspeakers are highly nonlinear systems and generate distortion in the output signal that limits the maximum sound pressure level and the quality of the reproduced sound. A control system can cancel those nonlinear distortion and generate a desired linear behavior between input signal $w(t)$ and sound pressure $p(t)$ at low and high amplitudes (Figure 2).

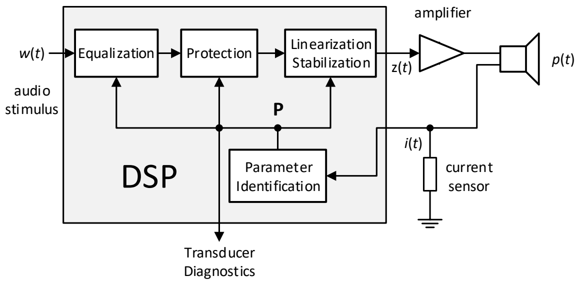

Figure 2: Components of a speaker control system

The control algorithm combines an active linearization with protection of the passive system against thermal and mechanical overload [4][5], equalization of the frequency response and stabilization of the voice coil position.

These features lead to an extension of the usable working range to increase low frequencies and overall sound pressure level or allow transducers to be made smaller, lighter and more cost effective. Additionally, transducer design can focus on increased efficiency by exploiting nonlinear motor structures and softer suspension systems to create a new generation of *Green Speakers* [6][7] producing more acoustical output and less heat by requiring less energy.

A control algorithm such as a mirror filter [8] exploits the results of electro-acoustical modeling using lumped transducer and system parameters, which can easily be interpreted and have a high diagnostic value.

2.2 Adaptive Control

Loudspeakers are manufactured with production variances [9][10][11][12][13] and change their properties over time due to heating, aging, climate and other external influences. The linear, nonlinear and thermal parameters of the loudspeaker can be identified by a pure electric measurement of voltage and current at the speaker terminals and used for adaptively updating the nonlinear control system while reproducing an ordinary audio signal (music, speech) [14]. Such an adaptive nonlinear control system simplifies not only the tuning of loudspeakers to a desired target frequency response (e.g. Butterworth alignment) but also guaranties constant transfer response over the lifetime of the product.

3 On-Line Diagnostics

Although the properties of the loudspeaker system are permanently measured by adaptive nonlinear control, the parameter and state information reveal not only the response of the loudspeaker to any audio stimulus but also the influence of climate [12] and acoustical load. In Figure 3 the influence of ambient temperature on thermal (coil temperature), electrical (power) and mechanical (resonance frequency) parameters and states is illustrated.

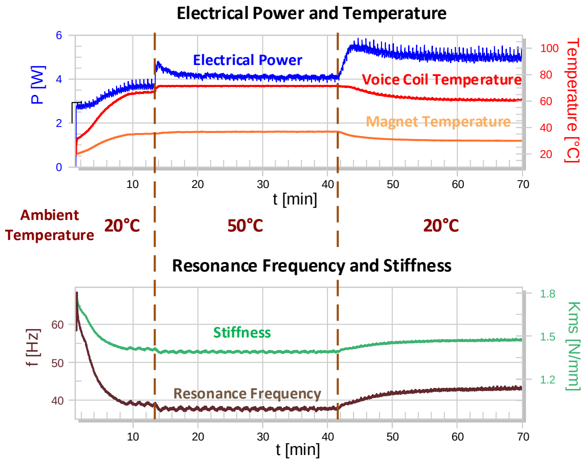

Figure 3: Temperature dependent transducer states and parameters

For example, the adaptive system can detect a leak in the enclosure which may reduce the total stiffness at lower frequencies and generate turbulent noise, eventually. Furthermore, the offset x_{off} in the voice coil rest position and nonlinear stiffness characteristic $K_{\mathrm{ms}}(x)$ shows the fatigue and the natural aging process of the mechanical suspension. This information is relevant for assessing the reliability of the passive loudspeaker parts and can give early indications of defects which may eventually lead to a complete breakdown of the system.

3.1 Parameter Interpretation

This section lists properties of active loudspeaker systems that can be checked by nonlinear adaptive control monitoring voltage and current only. Parameters having a high diagnostic value and that are easy to interpret are discussed. They are most relevant for assessing the reliability of the product and for detecting defects in the audio system.

3.1.1 Linear Parameters

The following linear parameters [15] in the electrical domain can be identified. Most important are:

R_e - input resistance at low frequencies: reflects connection problems to voice coil, partially shorted coil windings, and average temperature of voice coil. An open loop or short circuit condition can be identified.

$K_{ms}(x=0)$ – mechanical stiffness including enclosure and stiffness of suspension system at the rest position:

reflects softening due to mechanical stress (stretching of material), aging process and temperature dependency of the suspension material.

f_s –derived from $K_{ms}(x=0)$ assuming constant mass.

f_b – box resonance for vented enclosures: reveals tuning problems of enclosure, blocking of vented ports.

Q_{es} – electrical quality factor: indicates a demagnitization caused by overheating the magnet material (e.g. NdFeB)

Q_{TS}, L_e, C_{mes} and other linear parameter do not reveal relevant defect symptoms.

3.1.2 Non-Linear Parameters

Non-linear speaker control solutions can identify the elements of the non-linear equivalent electrical circuit of an electrodynamic speaker mounted into an enclosure [16]. Most non-linear parameters depend on excursion x. Important parameters for testing purpose are:

$K_{ms}(|x|>>0)$ – Stiffness of suspension at high excursion: indicates weakened or broken surround and spider [17]. This is a severe damage to the speaker since the restoring force keeping the coil in the gap will decrease and the excursion will rise.

x_{off} – offset in the voice coil rest position, derrived from $Bl(x)$ curve: reveals a shift of the $Bl(x)$-curve due to production variances, gravity, barometric air pressure differences between both sides of the diaphragm, aging and other external influences. The shape of the $Bl(x)$ curve is almost time invariant, because the voice coil height and gap depth are usually not changing.

This offset may increase the asymmetry of the nonlinear parameters, causes additional nonlinear distortion and reduces the maximum peak excursion. Adaptive non-linear control can detect an offset x_{off} exploiting the nonlinear distortion found in electrical input current. Using a DC coupled amplifier this offset can be compensated by adding a small DC compensation voltage U_{coil} to the audio signal.

U_{coil} – DC stabilization voltage: related to the stiffness of the suspension at very low frequencies. This is important for assessing the fatigue of mechanical suspension if the transducer is operated in an almost sealed enclosure where the acoustical stiffness is dominant.

$L(x)$ – Inductance depending on excursion: indicating the polarity of the transducer connection based on the typical asymmetry found in transducers which do not use additional shorting material (e.g. copper cap on the pole tips) where the inductance increases for negative coil displacement.

Other nonlinear parameters may also be used for defect analysis but are of minor general importance.

3.2 Interpretation of States

The adaptive, nonlinear control generates the internal states (e.g. displacement, temperatures) at high accuracy based on lumped parameters that are constantly beeing updated.

3.2.1 Voice Coil Displacement

For non-linear parameter identification, the states that excite non-linearities (e.g. displacement x, velocity v) need to be assessed as accurately as possible. This provides a reliable monitoring of the excursion for test applications such as waveform, rms and peak displacement.

The absolute voice coil position and the relative displacement can be measured by sensing the back EMF generated by the transducer.

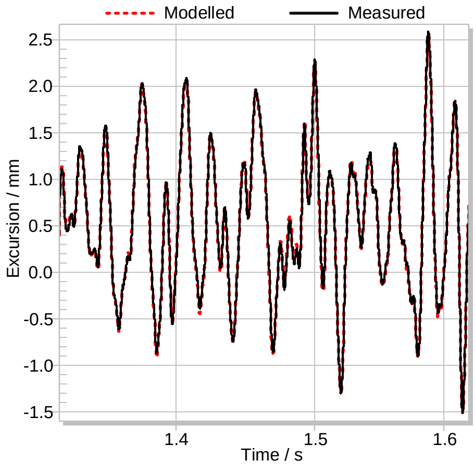

Figure 4: Voice coil excursion detected by using the adaptive model with current monitoring compared with the results determined by a Laser vibrometer

For example, Figure 4 shows agreement between the displacement signal modelled in the control system and measured by a laser while reproducing a music signal. Thus, speaker control can provide accurate excursion data in real time. A physical laser sensor is expensive and not practical for in-situ car tests.

3.2.2 Voice Coil Temperature

By having access to electrical input signals (voltage, current), the input power and temperature can be derived and monitored. A thermal model [18] that considers the heat flow from the coil to the ambience can be used to identify thermal resistance and capacity of the coil and other parts in the transducer. Although not directly related to defects, such data is important for long term diagnostics and root cause analysis.

3.3 Validation

For any parameter and state identification, the accuracy and hence validity needs to be assessed. This is usually done by an error criterion that compares a modelled and measured signal. If the error is small for higher level broadband audio signals, the derived parameters are considered valid.

A nonlinear control system models the relationship between terminal voltage and input current. The difference between measured and modelled input current is used as an error signal that is permanently minimized by adaptive parameter estimation.

The error signal may also be used as an indication for loudspeaker defects and symptoms that cannot be modelled, for example a rubbing coil, a loose connection or the influence of abnormal acoustical or mechanical load changes.

3.4 Restrictions of Electrical Testing

Loudspeaker control is restricted to electrical signals. Thus, any defect that affects the coil vibration in a relevant way produces a back-induced voltage and could be detected. However, there are some critical defects that do not affect the coil vibration in a significant way, such as:

- Transducer defects: slightly rubbing coil, buzzing wires, open joints due to gluing problems or loose particles. Those defects are typically expressed as *Rub&Buzz* symptoms. Even a well-tested (prior to mounting) transducer may develop such defects over its lifetime.
- Rattling / parasitic vibration problems: panels or similar structures that are excited by the transducer’s mechanical vibration (usually in close proximity) or by acoustical excitation (at any position in a car cabin due to pressure at low frequencies) may produce an undesirable sound.
- Small leaks (holes, vents) in enclosures may produce turbulent symptoms in sound pressure but usually cannot be identified through the input terminals of the loudspeaker. Those symptoms correlate with the sound pressure in the enclosure (not the radiated sound!).

The detection of such defects requires, in most cases, an acoustic sensor (a microphone).

4 Extension of Acoustic Testing by Electrical Loudspeaker Control

Acoustic sensors may be used to supplement the self-test capabilities of the audio device. That allows the detection of defects that cannot be directly assessed from an electrical measurement.

In many audio devices, microphones are available (e.g. in car for free speech or active noise cancellation application, mobile phones or smart loudspeakers). Although those sensors are not selected and not qualified for test purposes and the performance will be compromised due to the position, signal-to-noise ratio and bandwidth, they can at least be used for qualitative defect detection [1].

Most acoustic defect symptoms of *Rub&Buzz* and parasitic vibration are impulsive and have higher frequency content [19]. Usually they are excited by high displacement (high mechanical energy) at low excitation frequencies.

In an example using traditional test equipment, a sine chirp was used as a test signal. Through a microphone-based test, the *Rub&Buzz* symptom (black curve in Figure 5) shows strong peaky defect symptoms below 100Hz.

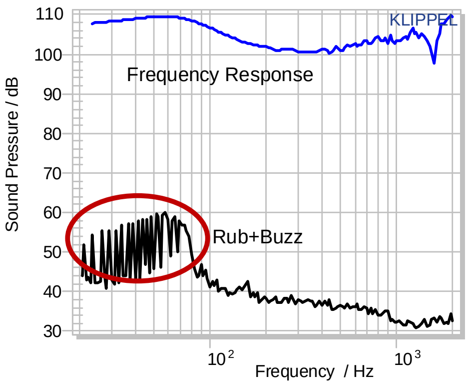

Figure 5: Rub&Buzz Symptom of a defective loudspeaker

The combination of acoustic measurement and displacement modelling by loudspeaker control is very effective.

In Figure 6 the excursion waveform is shown versus the chirp frequency. The black colour indicates a high crest factor (>12 dB) of the high-passed microphone signal [4]. Consequently, in addition to the result in Figure 5, the critical excursion that causes the defect symptom can be assessed. It was found at +1.3 mm.

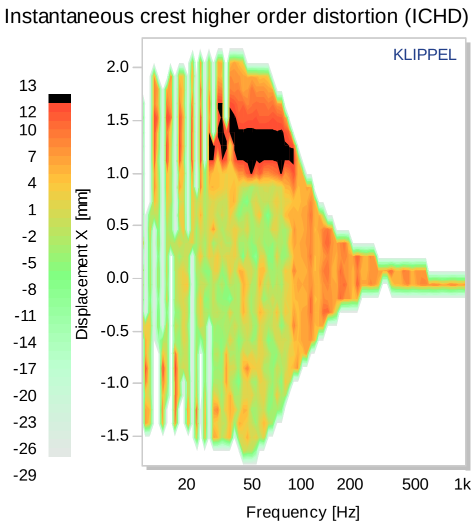

Figure 6: Crest factor analysis of a defective loudspeaker versus frequency and excursion

The mapping of the defect symptom to the actual excursion provides valuable root cause information. In this example the loudspeaker cone touched a connection cable at +1.3 mm of outward excursion.

However, during the normal operation of a car by the end user, other acoustic symptoms may mask or falsify defect symptoms:

- Ambient noise (e.g. engine, road, wind)
- Passenger talk, noise
- Audio playback by sound system

Such noise may also be impulsive, quite similar to defect symptoms. Thus, the measurement of impulsive symptoms shall be done under well-controlled and undisturbed conditions only.

5 Car Testing Applications

The test methods presented so far can be applied to any audio system with loudspeaker control and built in microphones. In this paper we focus on typical test applications inside a car.

5.1 Design / Development Phase

The first step in the product cycle is the development phase. Although the audio system with loudspeaker control for the product under development is not finished yet, the design can benefit from previous products, which provide long term data, typical defects caused by design problems or new, unexpected use cases. On-line monitoring of loudspeaker parameters and states provide abundant real-world data under many different conditions. A feedback loop from existing product experience to new product development is hereby made possible.
Adaptive loudspeaker control can compensate production variances and tune the overall performance to a target. Thus, costly optimization of admissible tolerances can be reduced to a minimum.
Furthermore, time variant properties of loudspeakers are also compensated, which eases the development considerably.
A major benefit is the actual testing during the design phase. Presented methods, especially in combination with acoustic sensors, can be applied for robustness and reliability checks (maximum level testing, temperature, humidity, shock, acceleration, accelerated life tests, etc). Tests provide comprehensive data instead of a simple pass/fail decision for test compliance. A typical example for the variance of resonance and suspension stiffness during temperature variation tests is illustrated in Figure 3.

5.2 End-of-Line Quality Control

As previously stated, production variances can be compensated by loudspeaker control. However, from a production point of view, the actual variances are an important indication for production consistency [13]. This correction data can be also provided by loudspeaker control.
Two basic options can be applied to End-of-Line (EoL) tests:

1. Electrical testing by loudspeaker control: Unattended, automatic operation is a significant benefit. No external test equipment is required for electrical testing. Defects mentioned in Chapter 3 can be detected. However, acoustic problems may not be detected, see chapter 3.4.
2. Comprehensive in-situ tests using external analyzers [1][19][20] with additional diagnostics from loudspeaker control (e.g. displacement monitoring): Integrated or dedicated test microphones may be used. Electric and acoustical defects can be detected; root cause analysis is significantly improved by electrical diagnostics.

Test results may be stored internally or transmitted to outside data storage and analysis equipment for statistical post processing and pass / fail decision.

5.3 Long-term Evaluation

Since the test system is integrated in the audio device, it can constantly monitor the electrically accessible performance, parameters and states. Thus, testing in the field is not restricted to service stations anymore.

Defective loudspeakers identified during normal use can be switched off so they do not severely impair the overall performance of the complete audio system.

Even more convenient, early symptoms of defects based on continuously acquired test results can generate warnings or error messages to the end-user before they become audible or critical.

Non-critical conditions may simply be stored and read out during regular service, and predictive maintenance can be applied (depending on brand and vehicle type).

Loudspeakers may also be set into an "Emergency mode": If parameters exceed certain limits (e.g. $K_{ms}(0) < 0.4$ N/mm or acoustic defects occur at $x > 2$ mm). Reducing the maximum allowed excursion in the protection system will extend the remaining product life and prevents a critical total failure of safety relevant loudspeakers used as a pedestrian warning system.

5.4 Service Station

A comprehensive test can be performed at the service station as well, with all features discussed in the EoL section 5.2.

Data obtained from long term evaluation (section 5.3) should be read out and stored in a cloud or similar data storage and assigned to the vehicle ID number. Statistical investigations could reveal valuable data for root cause analysis, which could be used for the development of the next generation products.

5.5 Safety Related Monitoring

Sound sources and sensors are also used for safety related applications such as pedestrian warning systems or vehicle movement alerts. Such components require special monitoring methods. Loudspeaker control constantly verifies proper operation while they are in use (radiating or recording sound). In some cases, such components are used randomly and rarely (e.g. acoustic indication for driving in reverse) but a consistent operation is mandatory. Thus, they need to be tested constantly, even when not used, without noticeable acoustical symptoms for the user.

Speaker control can permanently monitor transducers based on an inaudible low frequency tone and set error conditions accordingly.

6 Conclusions

Exploiting new loudspeaker control methods for test and measurement applications is a useful strategy. Almost as a by-product, comprehensive diagnostics information can be gathered. Just from electrical monitoring (voltage and current), many defects in the final application can be detected on-line and, in some cases,, even before the user will notice it. Typical defects include connection problems (open or loose connection), shorted coil or cables (fully or partially), aging symptoms and enclosure changes (e.g. blocked vents). Such monitoring results can be stored and read out for service and diagnostics, or in case of a "connected" car, they can be automatically transmitted to the manufacturer.

Displacement modelling inherent in loudspeaker control provides easy access to the mechanical behaviour and can be considered a smart sensor. It can be used to control peak displacement in case of problems with the loudspeaker to at least maintain some of the output until the part can be replaced. This is especially important for safety related components.

The combination of electrical testing with acoustic sensors mounted in a car for free speech or ANC applications results in a comprehensive test system. Although the performance of built-in microphones is limited, noticeable defects can still be identified reliably. By mapping the excursion of the voice coil to defect symptoms, further diagnostics for root cause analysis can be extracted.

Acoustic tests are much more susceptible to disturbances and require low ambient noise conditions. Thus, the proposed method of acoustic tests with loudspeaker control extension can only be applied to end-of-line tests or testing under well-defined conditions.

Further investigations are required to isolate acoustic defect symptoms from other similar ambient noise. This would allow not only online electrical monitoring in the final application while driving a car but also an acoustic monitoring of the audio system.

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