Auralization – Subjective Evaluation of Speaker Distortion

Wolfgang Klippel, Klippel GmbH, Dresden, Germany, www.klippel.de

Abstract: A new auralization technique is presented for the objective and subjective assessment of drivers in the large signal domain. Using the results of the large signal parameter identification a digital model of the particular driver is realized in a digital signal processor (DSP) to simulate the sound pressure output for any given input signal (test signal, music). This technique combines objective analysis and subjective listening test to assess the linear and distortion components in real time. This valuable tool shows the impact of each distortion component on sound quality and allows driver optimization with respect to performance, size, weight and cost.

Introduction

Loudspeakers which have similar small signal characteristics may sound quite different at higher amplitudes. Thermal and nonlinear mechanisms determine the maximal output of the driver and cause signal distortion. Most common measurement techniques valuate the performance at minor amplitudes. Assessing the driver in the large signal domain says more about the performance of the speaker under normal working conditions. Loudspeaker are expected to be able to reproduce the sound as loudly as possible with low distortion. Cost, sensitivity, size and weight are other constraints which are directly related to the large signal performance. There are different objective approaches to measure the performance objectively. Harmonic and intermodulation distortion measurement show the effect of the nonlinearities for a special excitation signal. Nonlinear and thermal parameters show the physical causes of the distortion and are crucial for the driver design. However, the results of both measurements do not reveal the impact of the distortion on subjectively perceived sound quality. There are many other questions in the gap between subjective and objective assessment:

- How sounds the distortion components produced by the separated nonlinearities?
- How can we mask distortion to make them less audible?
- What is the most critical program material in listening tests?
- Are there any desired effects of nonlinear distortion?
- How can the performance/cost ratio be increased?
- What are the benefits of some additional efforts?
- How does the driver sound after optimization?

In order to give answers to this question we will present a new auralization technique which combines objective distortion measurements on audio signals in real time with a tool for performing systematic listening tests in the large signal domain. After giving a summary on large signal modeling we will apply this technique to artificial and natural sounds and will discuss the relationship between objective parameters and subjective sensations.

Loudspeaker Modeling

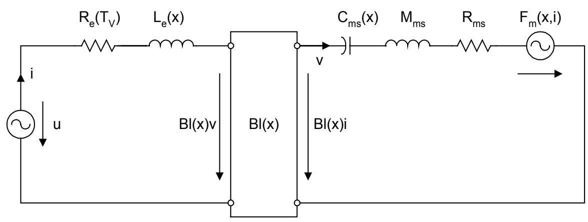

Fig. 1. Large signal model of the driver

To model the dominant nonlinearities of the driver at high amplitudes this model considers the variation of the force factor *Bl(x),* the stiffness $K_{ms}(x)$, and the inductance $L_e(x)$.

The electromechanical equivalent circuit corresponds with the following set of nonlinear differential equations:

Figures 2 shows the *Bl*-product of a driver measured by a dynamic identification technique (Distortion Analyzer [1]) and used as an example in this paper. Due to the short voice coil overhang the curve has a distinct maximum at 1.2 mm and decreases rapidly for positive and negative displacement.

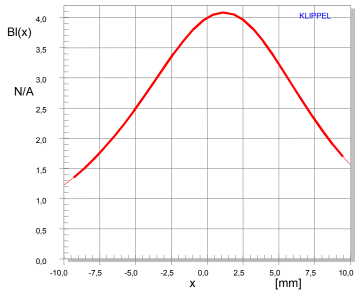

Fig. 2. Bl-product versus displacement x

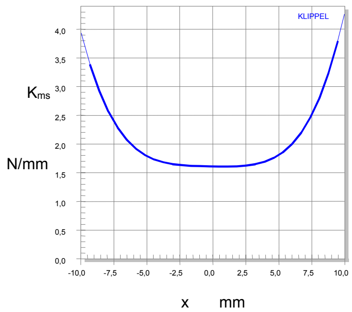

Fig. 3. Stiffness $K_{ms}(x)$ versus voice coil displacement x

The mechanical suspension of the example driver is represented by the stiffness $K_{ms}(x)$ seen in figure 3. At higher amplitudes the stiffness increases rapidly indicating high mechanical load in the suspension.

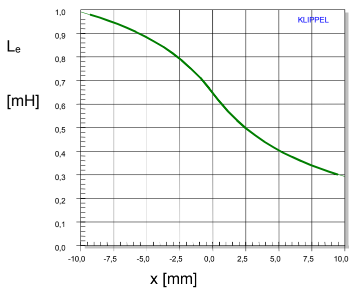

Fig. 4. Voice coil inductance $L_e(x)$ versus displacement

The strong asymmetry of the inductance nonlinearity $L_e(x)$ shown in figure 4 is typical for drivers without short cut ring and pole cap. If the coil moves between pole plate and back plate (coil in) the inductance will be much higher than in opposite direction (coil out) where the magnetic field finds a much longer air path.

Speaker Auralization- How it Works

In order to synthesize the loudspeaker output for any input signal in real time the set of nonlinear differential equations is transformed into the digital domain and implemented in a digital signal processor. Generating an identical copy of the driver in the digital domain makes it possible to check validity of the physical modeling, the nonlinear parameter measurement and the numerical calculations. Above that the digital modeling allows to modify the nonlinear transfer response of the driver virtually in order to investigate the effect of each nonlinarity systematically. There are two different ways for this modification:
In the simulation we would change the parameters of the driver and investigate the effect in the radiated output. The simulation is perfect for investigating design choices and to predict the performance of an improved design before the first prototype is finished. However, switching off the nonlinear parameters or any changes of the parameters will result in a different driver.
In the so called auralization we do not modify the properties of the driver investigated but enhance or remove the effect in the output signal. Thus the nonlinear differential equation and the parameters of the particular driver are kept unchanged during auralization. The equation produces internal state variables (displacement, velocity, temperature) of the real driver. The output of the digital model is the radiated sound pressure signal *p(t)* in the far field of. However, in the nonlinear differential equation the sound pressure *p(t)* is the sum of a undistorted output $p_{lin}(t)$ and the distortion components $p_K(t)$, $p_{BL}(t)$ and $p_L(t)$. The undistorted is linearly related to the drivers input *u(t)* and the distortion components $p_K(t)$, $p_{BL}(t)$ and $p_L(t)$ are generated by nonlinear subsystems representing the nonlinear stiffness, *Bl*-product and inductance, respectively (figure 5). The nonlinear subsystems are provided with the output $p_{lin}(t)$ forming a feedback loop, where the generated distortion components react to the state variables and their own generation process. This feedback loop explains the complicated behavior of the nonlinear system at large signals (compression, jumping effects). The Volterra series expansion, which corresponds to a feed-forward model, can not describe these mechanics precisely if the magnitude of the distortion components is of similar order as the magnitude of the linear input.

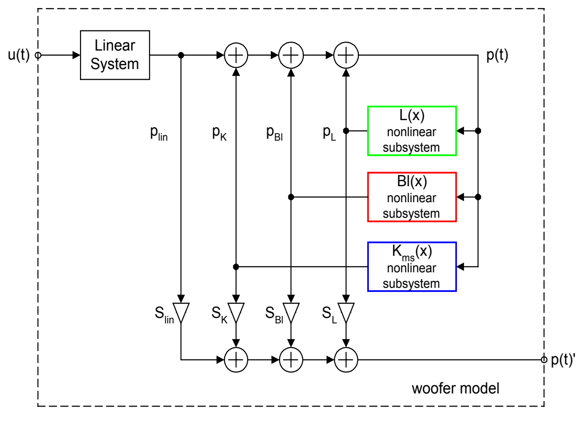

Fig. 5: Signal flow chart of the digital woofer model

In the digital model used for auralization we copy the summing point in the feedback loop by tapping the linear signal $p_{lin}(t)$, $p_k(t)$, $p_{Bl}(t)$, $p_L(t)$ and scaling them by the attenuators S_{lin}, S_K, S_{Bl}, S_L before summing up to the auralization output *p(t)'*. Changing the gain of the attenuators between 0 and 1 any desired ratio between the distortion components and the linear signal can be realized in order to determine the audibility of the distortion in listening tests. Clearly, setting all gain controllers equal one will yield the real driver output.
This topology of the driver model allows not only to adjust the magnitude of the distortion output. It allows also to measure the magnitude of the distortion components on-line while reproducing an audio-like signal. For such an input signal the distortion signals have a relative high peak value while the rms-value is much lower. Due to nonlinearity the crest factor in distortion components is much higher than in the original input signal *u(t)* or in the displacement signal *x(t)*. Setting the peak value of the distortion in ratio to the peak value of the total output signal p_{lin} is an appropriate measure for the contamination of the reproduced signal.
If the driver under test is intended for a woofer or subwoofer channel an additional tweeter path can be realized by using a crossover as shown in figure 6. The input signal is attenuated by the gain controller S_{in} to produce displacement x_{peak} that is typical for the application of the driver. The gain controller S_{out} applied to the output signal controls the volume of the sound at the headphone.

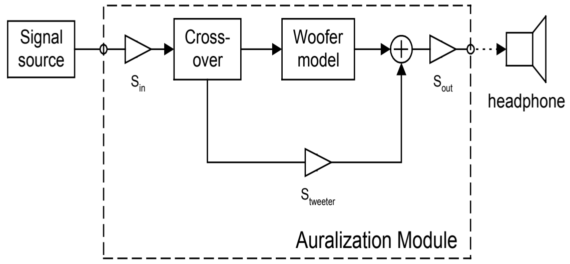

Fig. 6: Auralization of a woofer in multi-channel system

Performing Listening Tests

The Auralization technique allows performing systematic listening tests on loudspeakers to determine the audibility of the nonlinear distortion under normal conditions. These tests may be performed as blind or even double blind tests to avoid any bias and to check the reproducibility of the results.
Although, auralization technique makes it possible for the first time to measure the threshold of audibility in music, speech or other natural signals, the artificial test signals are also very interesting stimuli to become familiar with the character of the distortion and to use critical program material for which our ear is very sensitive.

Listening Examples

A practical demo of the auralization technique applied to artificial test signals and a representative music example may be found on the website **www.klippel.de.**

Conclusion

Nonlinear speaker auralization is a new technique for assessing the large signal performance of drivers by combining subjective and objective approaches. The loudspeaker model considering the dominant nonlinearities is implemented in a digital signal processor (DSP). This way the radiated sound pressure signal in the far field can be calculated in real time for any given input signal. The output signal is the sum of the linear system response and the distortion components separated for each speaker nonlinearity. Each signal component may be attenuated separately to investigate the impact on sound quality. The peak values of the driver state variables (displacement, temperature) and the distortion in the reproduced audio signal are measured in real-time and may be compared with subjective judgments. This model uses the results of nonlinear system identification (linear, thermal and nonlinear parameters) as parameter input.
The auralization technique allows non-destructive testing at the limits and beyond. This test shows the dominant source of distortion for the particular driver and is the basis for defining the permissible working range (maximal displacement X_{max}). The listening test may be organized as a blind or open AB-comparison between different modifications of the real driver in order to determine the threshold of audibility systematically. The auralization makes the effect of even small distortion audible where other forms of subjective testing are very time-consuming and give no reliable results. This information is valuable not only for high-quality speaker but for drivers with an optimal

performance/cost ratio as well. The auralization technique opens the dialog between engineers and users.

References

[1] W. Klippel, “Distortion Analyzer – a New Tool for Assessing and Improving Electrodynamic Transducers,” presented at the 108th Convention of the Audio Engineering Society, Paris, February 19-22, 2000, preprint 5109.

[2] W. Klippel, “Diagnosis and Remedy of Nonlinearities in Electrodynamical Transducers,” presented at the 109th Convention of the Audio Engineering Society, Los Angeles, September 22-25, 2000, preprint 5261.