Optimizing Transducer Design for *Klippel Controlled Sound (KCS)*

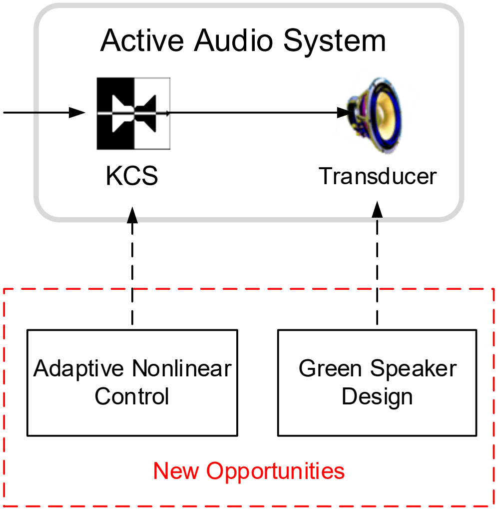
AN82

Application Note for KLIPPEL CONTROLLED SOUND (Document Revision 1.2)

SCOPE

This document explains KCS benefits, opportunities and limitations along with practical design rules and tools. Learn how to

- Generate more SPL at higher audio quality
- Reduce system size, weight and cost
- Improve product endurance and reliability
- Exploit opportunities of nonlinear transducer design
- Increase efficiency and voltage sensitivity
- Cope with Rub&Buzz and loudspeaker defects



DESCRIPTION

KLIPPEL Controlled Sound (KCS) is an adaptive nonlinear control software providing distortion reduction, voice coil stabilization, automatic alignment, and protection from mechanical and thermal overload to loudspeakers, headphones, and other actuators.

These software features give new opportunities in the design of the passive components (e.g., transducer, enclosure) for increasing efficiency and voltage sensitivity, which is the key for getting more acoustical output at higher quality from smaller speakers (Green Speaker Design). This application note discusses not only new ways to overcome physical limitations in traditional speaker design but also addresses other critical hardware problems (Rub&Buzz, endurance, fatigue) that cannot be fixed by digital signal processing, but have to be solved by hardware design and process control in manufacturing.

CONTENT

1 Introduction

1.1 Scope

DSP & Loudspeaker	Digital signal processing (DSP) provides new opportunities for sound reproduction. The loudspeaker transducer is still the weakest part in the audio signal chain, limiting the maximum sound output and generating undesired distortion. KLIPPEL Controlled Sound (KCS) significantly improves these shortcomings and provides new degrees of freedom in the design of hardware components (amplifier, transducer, enclosure, …).
Written for you?	This application note addresses engineers and other interested readers who have basic understanding of electro-acoustical modeling and common design concepts used for transducers and complete audio systems. All terms required for linear modeling valid at small amplitudes are defined in [5], [6], [7]. An easy introduction to the nonlinear modeling required at high amplitudes is explained in the tutorial [8].

1.2 What is KCS?

Software	KLIPPEL Controlled Sound (KCS) is an adaptive, nonlinear control technology based on physical modeling of the electro-dynamical transducer that can be implemented as software in available DSP platforms. KCS can be applied to any conventional moving-coil transducers used in loudspeakers, headphones, and other audio systems.
Linearization	KCS cancels the nonlinear distortion (harmonics, intermodulation) caused by the loudspeaker nonlinearities at high amplitudes that degrade the audio quality. It generates a linear overall system with a desired system response (e.g., Butterworth alignment).
Protection	KCS provides a predictive protection system avoiding mechanical and thermal overload while generating maximum sound pressure output with no or minimum latency.
Learning with music	KCS measures loudspeaker properties continuously during operation. It then adaptively compensates certain production variances, fatigue, climate and load changes over the product life. Thus, the frequency response of the system can be kept constant. Also, the voice coil can always be operated at the optimum position, which enables maximum peak displacement and bass performance.
more	A good overview of this powerful technology is given in the AES paper [*1*] freely available via open access (https://doi.org/10.17743/jaes.2020.0037).

1.3 What is Green Speaker Design?

New Paradigm	Green speaker design uses adaptive, nonlinear control for generating a required acoustical output with the expected audio quality while using a minimum of hardware resources (energy, material size, weight, manufacturing effort, cost, …).
More Efficiency	Contrary to traditional design where audio quality is traded with performance requirements, green speaker design maximizes the electro-acoustical efficiency of the loudspeaker while accepting nonlinearities and acoustical resonances in passive components. The resulting linear and nonlinear distortion from the passive system is instead cancelled actively by adaptive nonlinear control (KCS) implemented as software in a digital signal processor. This is the key to increase the total output, reduce the size of the system or reduce cost.
Workflow	While this application note focuses on essential design criteria, a more detailed description of the workflow is given in [2], Section 7.

2 Maximum Sound Output

"LOUD"speaker	The maximum sound output is one of the most critical performance characteristics limited by the size, weight, energy consumption and cost of the product.
Definition	The IEC standard IEC 60268-21 [9] defines the maximum acoustical output by the following characteristics: • Rated maximum sound pressure level SPL_{max} (section 18.2) at a reference point $\mathbf{r}_{ref}$ for a broadband stimulus (e.g. noise representing typical program material) The spectral properties and distribution of the sound in the 3D space are defined by the following characteristics: • Transfer function $H(f,\mathbf{r}_{ref})$ between electrical input and sound pressure output at a reference point $\mathbf{r}_{ref}$ (section 19) • Acoustic output power (section 20.3) • Directivity (section 20.2)
Physical Limits	The maximum sound output of an audio device is limited by the following physical constraints: • Transducer and speaker dimensions • Heating of the transducer, enclosure, amplifier caused by dissipation of electrical input power • Electrical power, voltage, and current provided by the amplifier • Battery capacity in portable devices • Displacement limited by the mechanical suspension in the transducer • Deterministic nonlinear distortion generated by transducer nonlinearities • Impulsive Distortion generated by irregular vibration (Rub&Buzz) • Fatigue, aging, and endurance (climate, load)
Valuable Standardized Metrics for Design and Performance Assessment	The following standard characteristics are useful to describe the physical causes limiting the sound output: Heating, cooling, thermal dynamics (according to IEC 60268-22 [11] section 24) • Increase of the voice coil temperature ΔT_v(t) (section 24.2) • Thermal resistance R_{TV}(t) (section 24.3) • Thermal time constants of the voice coil (section 24.5) Electrical input power • Real input power P_e(t) (IEC 60268-22 [11] section 17) • Peak voltage u_{peak} and peak current i_{peak} Electro-acoustical efficiency (IEC 60268-22 [11] section 21) • Reference efficiency for broadband stimulus η_r (section21.1) • Passband efficiency η_0 (section21.2) Voltage Sensitivity (according to IEC 60268-21 [9]) • Reference Sensitivity $L_r(u_{ref},\mathbf{r}_{ref})$ (section 22.1) • Passband sensitivity $L_0(u_{ref},\mathbf{r}_{ref})$ (section 22.2) Voice coil displacement (according to IEC 60268-22 [11]) • Peak and Bottom displacement $x_{peak}(t)$, $x_{bottom}(t)$ (section 19) • DC displacement $x_{DC}(t)$ (section 19) • Initial coil rest position X_0(t=0) (section 23) • Clearance to the boundaries X_{clear+}, X_{clear-} (section 23) • Offset x_{off} of the reference coil rest position (section 23) • Mechanical limited peak displacement X_{mech} (section 23.5.2) • Distortion limited peak displacement $X_{max,d}$ (section 23.5.3.2) Regular nonlinear distortion (according to IEC 60268-21 [9]) • Total harmonic distortion THD (section 21.4) • Maximum sound pressure level SPL_{THD} limited by THD (section 21.6)

	• Equivalent input harmonic distortion EIHD (section 21.7) • Two-tone Intermodulation distortion (section 22) • Multi-tone distortion (section 23) Impulsive Distortion generated by irregular vibration (Rub&Buzz) (IEC 60268-21 [9]) • Impulsive distortion level *ID*(*f*) (section 24.1) • Maximum impulsive distortion ratio *IDR*(*f*) (section 24.2) • Crest factor of impulsive distortion *CID*(*f*) (section 24.4) Fatigue, aging and endurance (climate, load) (according to IEC 60268-22 [11]) • Stiffness versus accumulated work (section 25.1.2) • Stiffness versus ambient temperature (section 25.1.4)

3 Efficiency and Voltage Sensitivity

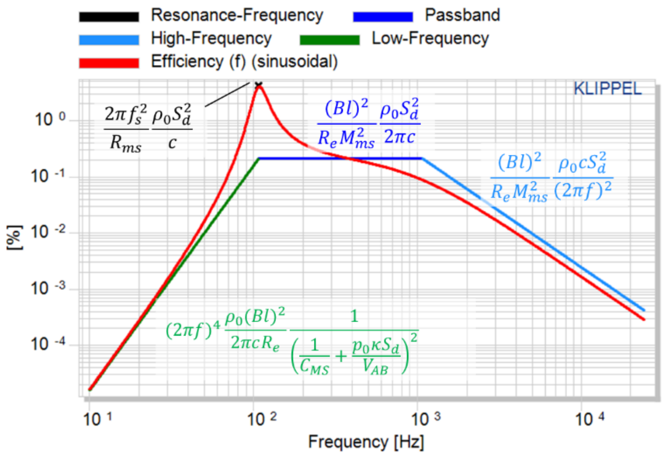
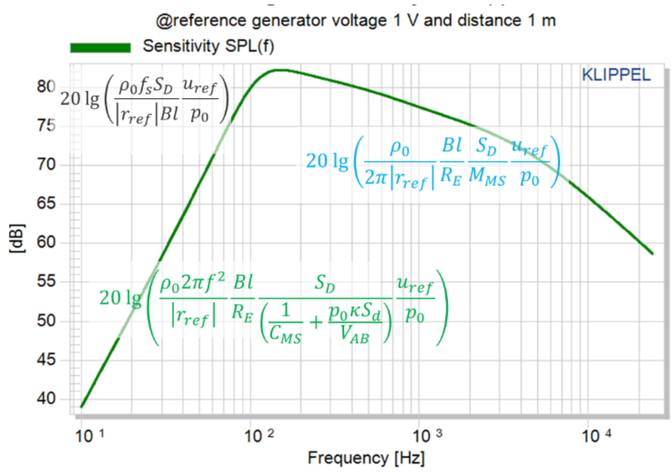
Different Terms!	Efficiency and voltage sensitivity are useful characteristics explaining how electrical input power and terminal voltage relate to acoustical output. This section shows the relationship and differences of the two terms based on standard definitions.

3.1 Reference values for a broadband stimulus (e.g., music)

Reference Efficiency	The standard IEC 60268-22 defines the reference efficiency for a broadband input stimulus (audio signal such as music or test stimulus such as noise, multi-tone complex) as $$\eta = \frac{P_a}{P_e} 100\%$$ This characteristic • Describes the acoustical output power P_a for a given electrical input power P_e • Depends on the spectral properties of the stimulus • Explains the heating in the transducer limiting the long-term output • Shows the input power provided from the amplifier • Determines power consumption and battery life in portable audio devices • Can be measured (KLIPPEL modules Live Audio Analyzer (LAA), Near Field Scanner (NFS)) • Can be simulated (KLIPPEL module *Linear Simulation* (LSIM)) based on transducer and enclosure parameters for any stimulus
Reference Voltage Sensitivity	The standard IEC 60268-22 defines the reference voltage sensitivity $L_r(u_{ref}, r_{ref})$ as the sound pressure level (SPL) obtained at a defined evaluation point (usually on-axis) at distance r_{ref} for excitation with a broadband input stimulus (audio signal such as music or test stimulus such as noise, multi-tone complex) with an RMS voltage u_{ref}. This characteristic • Is closely related to the transfer function between input voltage and sound pressure at the evaluation point • Determines the RMS and peak voltage requirements provided by the amplifier considering the crest factor of the stimulus • Is required for matching the nominal input impedance of the transducer to the voltage capabilities of the amplifier • Can be measured (KLIPPEL modules TRF, MTON, LAA) • Can be simulated (KLIPPEL module *Linear Simulation* (LSIM)) based on transducer and enclosure parameters for a given stimulus

Determined by the passive design!	KCS brings a lot of improvements to a loudspeaker system. Anyhow, it is still the passive system design (transducer + enclosure) that determines both efficiency and voltage sensitivity. Solely adding KCS to a system will not change this. But: KCS removes numerous boundaries on passive system design that can be traded for improving (passive) system efficiency. This is the core idea of green speaker design. More on this in 3.5.

3.2 Frequency Dependency

Valid for a Single Tone	Exciting the transducer with sinusoidal (single tone) stimulus reveals the dependency of efficiency and voltage sensitivity versus excitation frequency *f* as shown in the example below for a closed box system.
Efficiency versus f	
Voltage Sensitivity versus f	
Passband	At **high frequencies** above resonance frequency ($f > f_s$), efficiency and voltage sensitivity are closely related and have a similar frequency dependency. Both characteristics rise with • a larger value of the effective radiation area S_D • a smaller value of the moving mass M_{ms} • and a larger motor efficiency factor Bl^2/R_e resp. Bl/R_e generated by a higher force factor *Bl* and a smaller DC-resistance R_e Reducing the voice coil inductance by placing conductive material (e.g., shorting ring) close to the coil improves the voltage sensitivity with rising frequency but has only small impact on efficiency.
Around Resonance Frequency	At **resonance frequency f_s**, the voltage sensitivity and efficiency depend on the electrical and mechanical damping in the transducer: • A smaller mechanical resistance R_{ms} reduces the total damping and increases efficiency in all transducers. The voltage sensitivity also rises in transducers

(e.g., headphones) that have a negligible electrical damping due to a low motor efficiency factor Bl^2/R_e.

- The voltage sensitivity at f_s decreases with rising force factor Bl in transducers with a dominant electrical damping having a high motor efficiency factor Bl^2/R_e.

This has a fundamental consequence: A powerful motor realized by a large and expensive magnet increases the force factor Bl and generates a significant back EMF at the terminals (due to the large velocity in the mechanical system at its resonance). This makes it more difficult for the amplifier to generate an input current required to drive the mechanical system around the resonance frequency.

Bass Performance

At frequencies **below resonance** $f < f_s$, efficiency and voltage sensitivity are closely related and have a similar frequency dependency. Both can be increased by

- decreasing the mechanical stiffness K_{ms} if it is dominant compared to the stiffness of the air in the enclosure.
- a larger air volume V_B in a sealed enclosure if the air dominates the total stiffness.
- a larger motor efficiency factor Bl^2/R_e generated by a higher force factor Bl and a smaller DC-resistance R_e

Consequences for Transducer Design

Due to the frequency dependency described above, it is crucial to define the frequency range of the application before optimizing the transducer design. Further signal processing like equalizing and alignment may change the emphasis of the different frequency regions. The Linear Simulation Module (LSIM) may help optimizing design choices to meet a defined target performance. See chapter 3.4 for details.

Alignment

Additional to stabilizing the transfer function of the speaker over its lifetime, KCS also offers an automatic alignment feature to define the low frequency roll-off of the system. This may have a huge impact on the emphasis of the low frequency region and improvident use may lead to a huge boost in voltage and power requirements.

See Tutorial 4 of the KCS Monitor Manual for further information.

3.3 Matching Transducer and Amplifier

Problems and Solutions

The table below gives an overview of different symptoms that may occur due to poor amplifier and transducer matching and assigns solutions to either the amplifier or the transducer side. Usually, the latter is preferred due to lower cost.

LIMIT	REMEDY AMP	REMEDY TRANSDUCER
PEAK VOLTAGE	Higher Rail Voltage / Voltage Booster	Optimize Voltage Sensitivity
PEAK CURRENT	Additional Voice Coil / Amp Channel Bigger Amplifier	Increase R_e / Shift Voltage Sensitivity to Current Sensitivity
POWER	Bigger Amplifier	Optimize Transducer Efficiency
VOICE COIL TEMPERATURE	none	Optimize Transducer Efficiency

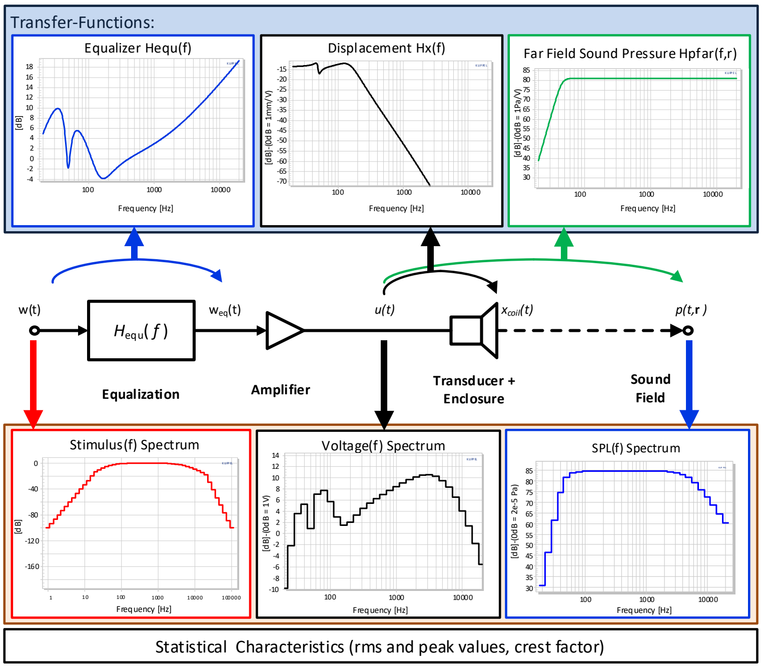
Note: Above symptoms may also be caused by excessive boosting of certain frequency regions due to alignment/equalization or other DSP algorithms.

Note: Above, a mismatch of amplifier and transducer leading to unused amplifier resources is not considered. In such a case it is recommended to increase the allowed voice coil's peak excursion or decrease the alignment's cut-off frequency to achieve the maximum SPL that the hardware allows. Eventual occurring peak requirements will be handled by the protection algorithms inherent to KCS.

<table>
<tr><td>Double Coil</td><td>The electrical input power can be doubled by using an additional amplifier connected to an additional coil available in double coil transducers.</td></tr>
<tr><td>DC Resistance</td><td>If the amplifier cannot provide either sufficient peak current or peak voltage, then a change of the wire diameter in the voice coil can improve the matching between amplifier and transducer. See section 6.2 for further details.</td></tr>
</table>

3.4 Predicting and Measuring Efficiency and Voltage Sensitivity

<table>
<tr><td>Design Tool</td><td>The Linear Simulation Module (LSIM) of the KLIPPEL Analyzer System is a dedicated simulation tool for defining the required efficiency and voltage sensitivity of the audio system to fulfill the target specification with respect to practical restrictions such as box size and amplifier. It helps to find optimum transducer parameters and the optimal geometry of the enclosure.</td></tr>
<tr><td>Input Parameters</td><td>The LSIM considers the following input information:

Linear, lumped parameter model for the transducer in the enclosure
Spectrum and crest factor of the stimulus representing typical program material (e.g., music or standardized test stimuli like defined in IEC 60268-21)
Desired target response of the overall system (e.g., Butterworth alignment) realized by automatic equalization
The target SPL_{max} at the reference point for the reproduced stimulus
</td></tr>
<tr><td>Results</td><td>


The LSIM provides the following results:

Efficiency and voltage sensitivity versus frequency
Efficiency and voltage sensitivity for the selected stimulus
Filter curve to equalize the passive speaker to the desired target alignment
Estimated peak and RMS values of important state variables (displacement, voltage, current)
The transfer function between input and output and other state variables
Spectra of the state variables for the defined stimulus
</td></tr>
<tr><td>Validity at High Amplitudes</td><td>The LSIM uses a linear model that allows fast simulations of the performance in the small signal domain. It is an easy way to assess new ideas and to compare design choices.
The results are also meaningful at high amplitudes, because KCS compensates transducer nonlinearities, heating and time variances. It linearizes displacement, velocity,</td></tr>
</table>

	acceleration and sound pressure by adding a *compensation signal* to the audio stimulus. Because the normal program material has a Gaussian-like amplitude, the linear model is a good approximation and the compensation signal has negligible influence on the calculated efficiency, voltage sensitivity and the RMS values of voltage and current. However, the linear model may generate significant deviations in the predicted peak values of voltage and current because the LSIM cannot consider the nonlinear compensation signal. Further, as a rule of thumb, a higher bass boost will usually lead to higher linear **and** nonlinear requirements. So, reducing the bass boost by a small amount may help decreasing amplifier demands significantly.
Measuring Accurate Values	Accurate peak and RMS values of voltage, current and other state variables such as electrical power and voice coil temperature can be measured using the KLIPPEL module *KCS Monitor*.

3.5 Paradigm Shift in General Design Rules

Traditional Design without KCS: **Compromise of efficiency, stability, alignment and distortion performance**	Traditional passive speaker design without adaptive, nonlinear control makes a compromise between efficiency and linear and nonlinear distortion to ensure sufficient audio quality at large amplitudes. Common design goals are e.g., a flat frequency response and weak nonlinearities in the intended working range. However, extending the linear behavior over a large amplitude range (e.g., by using a large voice coil overhang) and for typical program material (music) reduces the efficiency and voltage sensitivity because some resources (e.g., wires in the overhang coil) are not permanently used. In many applications a high and progressive suspension stiffness is used to prevent voice coil excursions exceeding the physical limits of the speaker since these could trigger damage or cause high nonlinear or impulsive distortion. This design approach significantly reduces efficiency and voltage sensitivity at low frequencies.
Design with KCS: **Efficiency first!** **(Distortion, stability, protection and alignment are taken care of by the controller)**	Green speaker design maximizes the electro-acoustical efficiency for a stimulus representing typical program material at maximum SPL, considering restrictions such as enclosure size, effective radiation area and amplifier limits. KCS adaptively equalizes the frequency response, compensates time-variance and cancels nonlinear distortion. Thus, resonances, nonlinearities and parameter variances of the passive transducer can not only be accepted but actively used since they open new opportunities to achieving higher efficiency. The active protection system keeps the peak values of displacement, voltage and current as well as the electrical input power and coil temperature within defined permissible limits. It achieves this by attenuating the stimulus primarily at frequencies where the electro-acoustical efficiency is low ($f < f_s$). This gives best audio quality and maximum SPL output by exploiting all hardware resources. Furthermore, since stabilization of the voice-coil position and protection from mechanical overload are taken care of by KCS, much softer and less progressive suspension designs can be used, which increases voltage sensitivity in the bass frequency region. KCS setup parameters such as protection limits can be modified without changing any hardware components.

4 Maximum Peak Displacement (X_{max})

4.1 Overview

Bass Performance	The maximum peak displacement X_{max} of the voice coil is an important characteristic for transducer and system design to realize the desired SPL at low frequencies. It is also a simple and transparent input parameter for KCS software specifying the permissible limits of the working range.
Definition	The maximum peak displacement X_{max} describes the maximum permissible peak value of the AC excursion limiting the acoustical output at low frequencies. According to IEC 60268-22 [11] it depends on the following characteristics: • Mechanical limited peak displacement X_{mech} (section 23.5.2) • Distortion limited peak displacement $X_{max,d}$ (section 23.5.3.2) • DC displacement $x_{DC}(t)$ (section 19)
Impulsive Distortion (Rub&Buzz)	The mechanically limited peak displacement X_{mech} considers the initial coil rest position $X_0(t)$, the offset x_{off} of the reference coil rest position giving the clearance to the boundaries X_{clear+}, X_{clear-} (see section 23 in [11]). It also considers impulsive distortion (IEC 60268-21 [9]) caused by irregular vibration (*Rub&Buzz*), overload, fatigue, and transducer damage, which degrade the audio quality significantly.
10 % Distortion	The distortion limited peak displacement $X_{max,d}$ considers a percentage value d (typically 10%) of total harmonic distortion $THD(f_s)$ generated by a single tone at the fundamental resonance f_s and intermodulation distortion $IMD(f_s, 7.5\, f_s)$ generated by a two-tone signal at f_s and 7.5 f_s. A percent value of d = 10% is used as a meaningful limit for the regular nonlinear distortion generated by force factor $Bl(x)$, stiffness $K_{mt}(x)$ (combined mechanical and enclosed air's stiffness) and inductance $L(x)$.
X_{DC}	The DC displacement $x_{DC}(t)$ is generated by transducer nonlinearities that rectify the AC stimulus. Although this low frequency distortion component generates no sound, it reduces the clearance to the boundaries and the amplitude of the AC displacement.
X_{offset}	X_{offset} is also a DC displacement of the voice coil. It summarizes all effects generating such a displacement not related to the transducer nonlinearities, e.g., gravity and fatigue.

4.2 Traditional Design Considerations for X_{max} (without KCS)

Keeping X_{max} small.	Traditional design without adaptive, nonlinear control tries to generate the required sound output with a minimum of voice coil displacement to operate the transducer in its linear region. In some applications, the required peak displacement X_{max} can be reduced by using multiple transducers or increasing the effective radiation area S_D to generate the same displaced air volume $X_{max}S_D$. A vented enclosure or an additional passive radiator can also reduce the voice coil displacement at the acoustical resonance. These approaches increase the size, weight, and cost of the product.
Ensuring Robustness	Nonlinear properties such as a progressive stiffness $K_{ms}(x)$ can be used as natural protection to keep the peak displacement $\|x\|$ below the mechanical limited displacement X_{mech} (defined in IEC 60268-22 [11]). This avoids impulsive distortion (Rub&Buzz), but generates more THD at lower frequencies.
Large Safety Headroom	A large safety margin $M = X_{mech} - X_{max}$ is required to cope with uncertainties such as DC displacements, offsets in the voice coil rest position, production/ageing-induced variances especially in the suspension and others.

Compromise in Audio Quality	Transducer nonlinearities such as force factor $Bl(x)$, inductance $L(x)$ and stiffness $K_{ms}(x)$ generate audible signal distortions at high excursions. The standard IEC 62458 [10] recommends a distortion threshold d=10% which corresponds to a maximum decrease of the force factor down to 82% or a maximum increase of the stiffness by up to 33% from its minimum. The distortion threshold d can be modified according to the expected audio quality. High quality products use a much more linear design while other products accept much higher nonlinearities for their application.

4.3 Modern Design Considerations for X_{max} with KCS

Exploit the Motor Nonlinearity Bl(x)	The active linearization can compensate significant variations of the nonlinear transducer parameters such as $Bl(x)$, $K_{ms}(x)$ and $L(x)$. Thus, the distortion limited peak displacement $X_{max,d}$ (see 4.1) becomes less important for ensuring audio quality. Consequently, a more nonlinear motor design using a lower voice coil overhang should be used to maximize the motor efficiency factor Bl^2/R_e (see 6.2). To avoid excessive peak voltage requirements for linearization (see next section), it is usually recommended that $Bl(X_{max})$ drops to approx. 50%...60% of the Bl(0) value.
Consider the Peak voltage	As discussed in chapter 3.4, the KCS compensation signal that is required for linearization increases if the transducer parameters become more nonlinear. Consequently, the selection of X_{max} may have a large impact on peak voltage requirements.
Avoid Hard Limiting	Like in traditional design, the maximum peak displacement X_{max} shall be smaller than the mechanical limited displacement X_{mech} defined in IEC 60268-22 [11] to avoid a generation of impulsive distortion, which has non-predictable and time-varying properties. Impulsive distortion cannot be canceled by signal processing.
Reduce the Safety Headroom	The active stabilization of the voice coil rest position in KCS, active canceling of the DC displacement, and the predictive protection system used in KCS keep the voice coil in the permissible working range $-X_{max} \le x \le X_{max}$.. Apply a safety margin according to the specification of your KCS library version (see section 7.2) to cope with small modeling errors which occur for instance because of unidentified production variances (e.g. moving mass M_{ms}).
Maximizing Displaced Air Volume	For maximizing the SPL at low frequencies, the displaced air volume $X_{max}S_D$ has to be maximized. Hence, if S_d shall be reduced in a new design, X_{max} must be increased accordingly to achieve the same SPL. In the special case of a speaker operated only below its fundamental resonance f_c, reducing S_d can increase the efficiency because the mechanical stiffness of the air reduces. However, a higher X_{max} is required to achieve the same displaced air volume. Efficiency at and above resonance drops significantly if S_d is reduced.

4.4 How to find the mechanical limit X_{mech} for KCS applications?

Select Golden Reference Units	The mechanical excursion limit X_{mech} considers the constraints of the mechanical system under the condition that the voice coil is at the optimum rest position. This is usually the case for a Golden Reference Unit representing an approved reference and the good units passing the end-of-line test in the mean. The excursion limit X_{mech} can be determined by tests applied to the Golden Reference Unit as described below.
Search for Impulsive Distortion	Measure the impulsive distortion using a sinusoidal sweep/*chirp* (according to IEC 60268-21 [9], use KLIPPEL TRF module) or using a multi-tone measurement technique (KLIPPEL KCS-ID module). A high impulsive distortion ratio in combination with a high crest factor (CID > 12 dB for chirp signal) indicates irregular vibration that limits the usable working range $-X_{mech} \le x \le X_{mech}$. The threshold T_{IDR} for the impulsive distortion ratio IDR can be adjusted in the range -50 dB < T_{IDR} < -30 dB for the chirp signal or -30 dB < T_{IDR} < -10 dB for the multi-tone signal to provide the best performance-cost ratio in the particular application.

Endurance Testing	Evaluate the reliability and endurance of the product under the influence of climate with typical program material while keeping the peak displacement in the usable working range $-X_{mech} \leq x \leq X_{mech}$. It is recommended to use the KCS system for such long-term testing because the active protection, stabilization, and linearization cope with parameter variations and avoid an overload situation.
Accelerated Life Testing	KCS also simplifies accelerated-life-testing to investigate the fatigue of the suspension in a shorter endurance test time (100 h). In this case, the amplitude of the test stimulus is increased to permanently activate the mechanical protection which increases the probability of high positive and negative displacement just below $\lvert x \rvert < X_{mech}$. KCS can also monitor the instantaneous displacement, temperature, and other state information and the parameter variations of the transducer during the endurance test.
Early Indications for Problems	The measurement of the impulsive distortion is repeated after the long-term test. A significant increase of the impulsive distortion ratio IDR, an increased offset in the voice coil rest position, and major changes in the nonlinear stiffness characteristic $K_{ms}(x)$ (besides expected break-in effects) are early indications for a low endurance, reducing the reliability of the product in the field.

4.5 Coping with Impulsive Distortion

Standard Test	The recommended way for assessing impulsive distortion is specified in IEC standard 60268-21 [9]. This measurement excites the transducer with a sinusoidal signal (chirp). It considers the fine structure of the distortion in the time domain whereas the total harmonic distortion (THD) and higher-order distortion assess the energy of spectral components averaged over the analysis window which is usually very low and close to the noise level.
Combining Measurement with Listening	The impulsive distortion can be separated from the desired signal and low-order distortion by calculating the residuum of the linear and nonlinear modeling. The fine structure of the residuum can be investigated by Time-Frequency Analysis (TFA) and subjective listening.
Practical Diagnostics	The impulsive distortion can be plotted versus the instantaneous displacement or sound pressure signals to understand the conditions under which clicks, noise, or other irregular vibrations are generated. This information gives valuable clues for identifying its root cause for and finding remedies for these critical problems. The practical diagnostics is discussed in the webinar *KLIPPEL LIVE section #10 Impulsive Distortion* in greater detail. The TRF and TRF STEP modules used as described in AN22 helps to measure Rub&Buzz and the related X_{max}.

4.6 Root Causes and Remedies for Impulsive Distortion (examples)

Signal Clipping	If the KCS in-/output or the amplifier exceeds its limits, the audio signal clips and generates impulsive distortion. Always make sure that the digital signals are below 0 dBfs and the peak voltage does not exceed the amplifier's ratings, set the built-in voltage limiter accordingly. The required state variables (digital level, voltage) are displayed in the KCS Monitor module.
Insufficient Clearance	Excursion limits caused by the back-plate, front-grill, lead wires or other mechanical parts generate deterministic clicks in the output signal. Asymmetrical limiting in either positive or negative direction can be caused by an offset in the voice coil rest position caused by design, manufacturing, or fatigue. The active stabilization in the KCS can be used to shift the coil to the optimal position increasing the maximum output. A similar offset found on the majority of all units shall be fixed by correcting the voice coil position in production. Symmetrical limiting indicates that the coil is at the optimum rest position and the maximum peak displacement X_{max} can only be increased by changing the design.

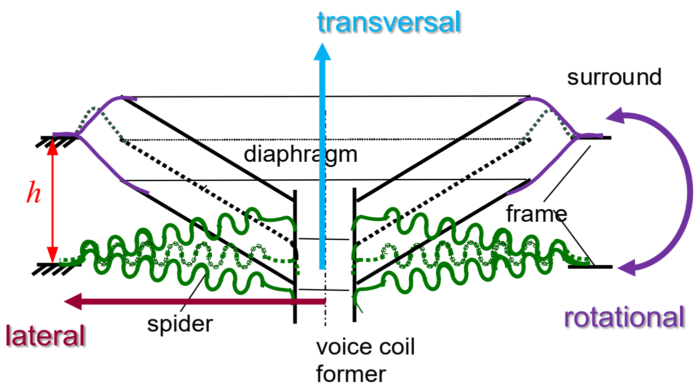
Voice Coil Rubbing	Voice coil rubbing is a random process that generates impulsive distortion that significantly reduces the audio quality and damages the coil wire insulation. This eventually leads to a total failure. This problem is often caused by *Rocking Modes* generated by imbalances in mass, stiffness, and force factor distribution leading to a tumbling movement of the voice coil. Speakers without a spider, like micro-speakers, tweeter, or head-phone drivers, are particularly prone to this problem. Increasing the gap-width might help but leads to sacrificing *Bl* and thus efficiency, solving the root cause of the problem is usually the better solution. Using a stiffer suspension material can reduce the rocking mode but increases the resonance frequency which is usually undesired. The RMA module identifies the imbalances (*M*, *K*, *Bl*) that are the root cause of the rocking and indicates the way how to fix the undesired problem.
Turbulent Air Flow Noises	The airflow can generate a modulated noise due to the turbulences occurring at high particle velocity in ports of vented enclosures and in the motor. This unpleasant sound can be reduced by decreasing the particle velocity, e.g., using a larger diameter and improved flare ratio of the port in vented systems. Additional venting holes in the voice coil former and magnetic system are helpful to reduce the noise generated in the motor, though this may reduce the forced convection cooling which is a desired effect for reducing the voice coil temperature. Another reason for airflow noise might be a leak of a sealed enclosure, either intentionally for pressure equalization or unintentionally from manufacturing. Such leaks should be damped. The Air Leak Stethoscope (ALS) of the KLIPPEL QC system might help you finding these airflows.
Rattling	Sometimes undesired noise does not originate from the transducer itself but from resonances or loose parts of the connected construction (e.g., enclosure). In this case, a better decoupling or a redesign of the construction is necessary. To suppress resonances a notch filter might help as well. Again, the Air Leak Stethoscope (ALS) of the KLIPPEL QC system might help you locate the noise sources.

5 Optimum Suspension Design for KCS Applications

5.1 Targets

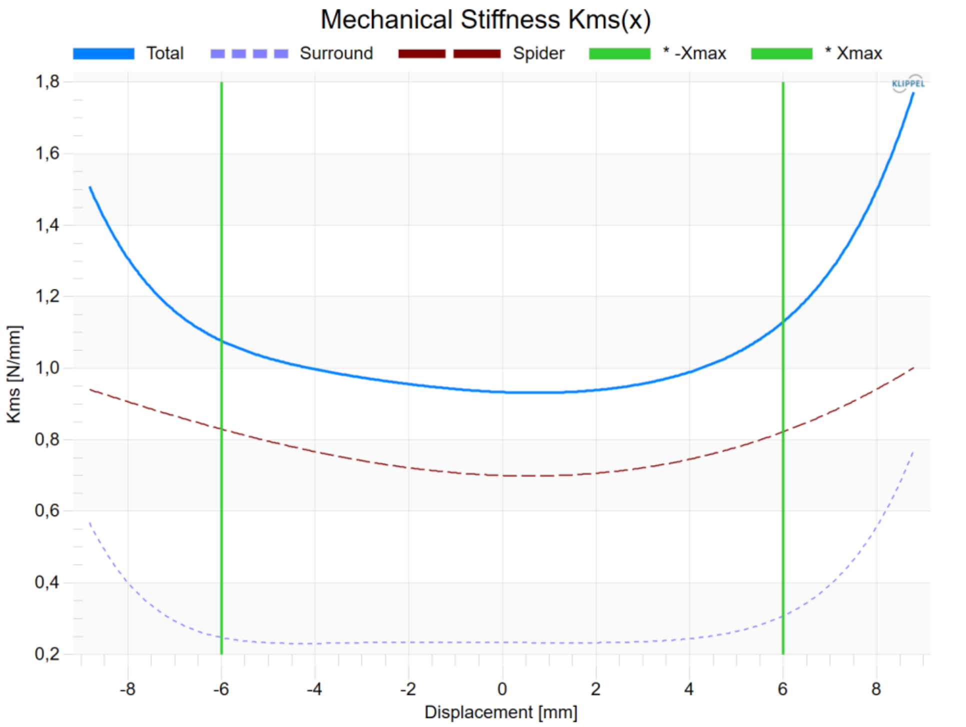
What KCS can do	The mechanical suspension is the most critical part of transducers. KCS technology gives new degrees of freedom for achieving the following objectives: • Maximum mechanical limited peak displacement to increase the maximum SPL at low frequencies • Lower transversal stiffness to increase the efficiency and voltage sensitivity at low frequencies • Self-protection capabilities of the mechanical suspension at high excursion $\|x\| > X_{max}$ • Improved endurance to cope with climate, fatigue, aging, and other external influences • Improved product reliability

5.2 Geometrical Considerations

Suspension Components	 The suspension system in the figure above comprises a spider and a surround connected via the voice coil former and driver frame.
Low Stiffness K_{ms}	The transversal movement in x-direction shall displace air and radiate sound. The transfer stiffness K_{ms} of the total suspension shall be low, while providing sufficient stiffness in other directions and fulfilling other important constraints (e.g., reliability). The spider usually provides most of the stiffness in the lateral direction required for centering the coil in the gap with sufficient clearance to avoid voice coil rubbing.
Rocking Modes	The rocking of the coil in the rotational direction is a cause for coil rubbing. The distance *h* between the spider and surround increases the rotational stiffness, which reduces the rocking amplitude and shifts the natural frequencies of the rocking modes to higher frequencies. The rocking modes of transducers using a single coil cannot be compensated by KCS or any other control technique. It is recommended to identify the amount and direction of the imbalances by the RMA measurement module and fix the root cause by reducing the imbalance. See Application Note 80, which is dedicated to this problem.
Surround	A high displacement at low frequencies generates significant deformations of the surround, which affects the sound radiation at higher frequencies. In a typical woofer, the geometry of the surround profile generates high intermodulation distortion at the first surround resonance typically found around 1 to 2 kHz which are not canceled by KCS. Choose a sufficient size and an appropriate profile of the surround.

5.3 Nonlinear Stiffness Characteristics

Total Suspension



The nonlinear stiffness $K_{ms}(x)$ versus displacement x can be measured over a wide amplitude range by using the initial identification (KCS-ID) and KLIPPEL LSI module.

The total stiffness $K_{ms}(x) = K_{spider}(x) + K_{surround}(x)$ is the sum of the stiffness components of the spider and the surround. The characteristics can be separated by performing an additional measurement on the modified transducer after removing 80% of the surround and predicting the two curves (see Application Note 2). The Suspension Part Measurement module (SPM) of the KLIPPEL Analyzer allows to measure nonlinear stiffness characteristic $K(x)$ of the component.

Avoid High Stress in Spider and Surround

In the example shown in the figure above, the spider has a much higher stiffness $K_{spider}(x) > K_{surround}(x)$ in the intended working range $X_{max} < x < X_{max}$ and is much more symmetrical than the surround. The stiffness of the surround is almost constant over the working range but rises steeply at positive displacement $x > 6$ mm. This indicates high stress in the surround material, which can speed up fatigue and reduces the reliability of the product if the transducer is operated without KCS.

Limit Peak Voltage Requirements

Although KCS can compensate a nonlinear stiffness characteristic, it is not recommended to let the stiffness rise by more than 15-20% within the working range. A nonlinear stiffness adds no value to a system where the excursion is already controlled by KCS, but may significantly increase peak voltage requirements due to the nonlinear compensation voltage.

5.4 Influence of the Enclosure Type

Transducers in Small Closed Boxes

In closed box systems the total stiffness is $K_{mt}(x) = K_{ms}(x) + K_{mb}$, comprising the suspension stiffness $K_{ms}(x)$ and the equivalent mechanical stiffness $K_{mb} = \frac{p_0 \kappa S_d}{V_B}$ of the enclosed air.

For very small box volumes V_B and large radiation areas S_d, the box stiffness K_{mb} becomes dominant and reduces the nonlinear variation in $K_{mt}(x)$ and the nonlinear KCS compensation signal. However, a high air stiffness significantly increases the voltage requirements when driven below the fundamental resonance f_c. $K_{mt}(x)$ should be as low and flat as possible to maximize efficiency.

A *closed* loudspeaker box must not be perfectly sealed to avoid large voice coil offsets caused by climate changes but require a barometric vent with a high time constant.

Transducers in Large Closed Boxes	Transducers mounted in large closed boxes (doors, trunk in cars) and baffle-like designs (e.g., Dipole loudspeakers) where the mechanical stiffness $K_{ms}(x)$ is dominant highly benefit from a flat stiffness characteristic and a low $K_{ms}(0)$, especially when driven below their fundamental resonance.
Transducer Exclusively Operated in the Passband	Midrange transducers, tweeters, shakers used on panel speakers are usually operated in the passband ($f > f_c$) where the voice coil displacement and the distortion of $K_{ms}(x)$ are small. A progressive stiffness is beneficial for those applications because it counteracts the variance of the voice coil rest position in production and over time. It is also helpful for reducing the DC displacement generated by other transducer nonlinearities (e.g., inductance $L(x)$).
Vented Box Systems	Enclosures using a vent or passive radiator reduce the voice coil displacement at the acoustical resonance f_b. A high-pass filter should be used for attenuating the audio signal at lower frequencies $f < f_b$ where the acoustical short-cut generates low efficiency and the voice coil displacement is high. Transducers with a progressive stiffness can be used in those applications because the influence of the stiffness is usually low as these systems are dominantly driven in the passband.

6 Optimum Motor Design for KCS Applications

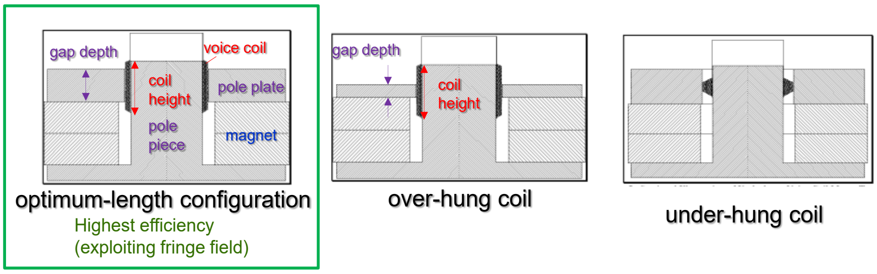
6.1 Targets

KCS provides new degrees of freedom for the design of the motor (voice coil, former, magnet, iron path, shorting-material) to achieve the following objectives:

- Increased motor efficiency factor Bl^2/R_e by using nonlinear motor topologies (e.g., small coil overhang)
- Reduced cost
- Reduced voice coil mass contributing to total moving mass M_{ms}
- Matching the transducer to the power amplifier
- Sufficient voltage sensitivity for canceling nonlinear distortion
- Reduced voice coil temperature by exploiting forced air convection cooling
- Sufficient clearance in the gap to avoid coil rubbing

6.2 Maximizing Motor Efficiency

Coil-Gap Topology Giving Maximum Efficiency



The relation between voice coil height h_c and gap depth h_g determines the linearity and efficiency of the motor. In traditional design, efficiency is traded for linearity by using an over-hung or under-hung configuration where the coil is either much longer or shorter than the gap depth. The optimum-length configuration uses a small overhang just sufficient to exploit the fringe field outside of the gap. This gives the highest motor efficiency and best voltage sensitivity. In traditional design these benefits are mainly exploited in low-cost applications where a reduced audio quality degraded by intermodulation distortion is acceptable.

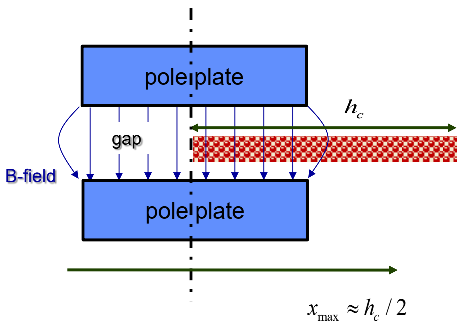
Pro and Cons

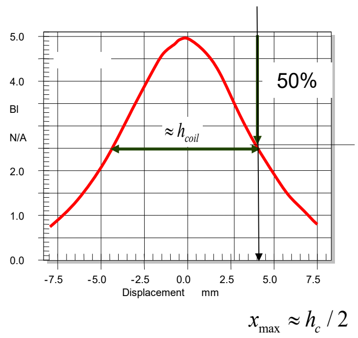
Topology	Optimum length	Over-hang	Under-hang
Efficiency	high	low	low
Moving mass M_{MS}	medium	high	low
Bl(x)-nonlinearity	strong	weak	weak
L(x)-nonlinearity	medium	strong	weak
DC-Stability	critical	robust	robust
Weight, size cost	low	medium	high

The table above summarizes the pros and cons of the most important coil-gap topologies. KCS exploits the early decay in the force factor *Bl*(*x*) of the optimum length configuration to detect the voice coil rest position at small amplitudes. The *Bl*(*x*) curve in the over-hung and under-hung configurations need more displacement to find sufficient *Bl*(*x*) distortion required for reliable detection of the voice coil rest position.

The active linearization and voice coil stabilization provided by KCS exploit the benefits of the optimum length configuration and generates more output and better audio quality compared to traditional designs.

Coil Height and Peak Voltage Requirements

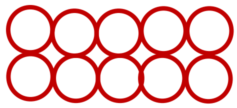
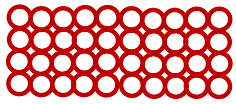




The coil height h_c limit the maximum peak displacement X_{max}. The force factor *Bl*(*x*) decays with displacement *x* when coil windings are leaving the gap. The activate linearization compensates for the decreasing force factor and cancels the distortion in the output. If half of the coil is still in the gap, the *Bl*(*x*) drops to approx. 50 to 60% from *Bl*(*x*=0) and an increase in the peak voltage requirement is still acceptable for most amplifiers (about 3dB). Thus, the coil height $h_c \approx 2X_{max}$ should be twice the maximum peak displacement X_{max} for KCS applications.

Gap Depth

After defining the coil height h_c, the gap depth h_g is found that gives maximum motor efficiency by operating the magnet at the optimum working point in the *B*(*H*)-characteristic. Neodymium which is often used in modern transducers as magnet material is a sensitive cost factor, while the pole and backplate, pole piece, and other soft iron parts contribute to the weight. An FEA magnetic design tool is required to find the optimum geometry giving maximum motor inductance *B* penetrating the coil at the rest position corresponding to a maximum motor efficiency factor Bl^2/R_e. This optimum gap depth is usually a little bit smaller than the coil height ($h_g \approx 0{,}9\ h_c$) to exploit the fringe field outside the gap.

Optimum Voltage Sensitivity	 Two layer voice coil  Four layer voice coil The voltage sensitivity can be improved by increasing the diameter of the coil wire. Using the same wire material and occupying the same volume V the electrical resistance R_e and the squared force factor Bl^2 will change in the same way without affecting the motor efficiency factor Bl^2/R_e. In practice, approx. 3 dB more voltage sensitivity can be generated by reducing the DC resistance R_e to half of the value. See section 4 of [2] for a detailed discussion on this topic.

6.3 Shorting Material

Transducer without KCS	Conductive shorting material (caps, rings) made of copper or aluminum are placed close to the voice coil to reduce electrical impedance at higher frequencies and nonlinear distortion generated by the voice coil inductance $L(x,i,f)$ which is a function of displacement x, current i and frequency f. These hardware solutions increase the cost of the product, require a compromise with motor efficiency, and give significant nonlinear distortion reduction only in a limited frequency range.
Design for KCS Application	The active linearization of the flux modulation represented by inductance $L(x,i,f)$ can provide better audio performance over a wide frequency range than the cost-intensive hardware solution. However, it is beneficial to apply the KCS technology to a transducer operated significantly above their resonance frequency using a simple, shorting ring made of light and inexpensive material (aluminum) placed on available space (below the gap) where the voice coil inductance $L(x)$ has a local maximum. The additional hardware component improves the voltage sensitivity and efficiency at higher frequencies while the active linearization ensures the optimum audio quality.

6.4 Voice Coil Material

Conductivity contra Density	The perfect wire material should have a low density but a high conductivity to maximize the motor efficiency factor and to minimize the moving mass M_{ms}.
Copper	Copper is almost two times more conductive than aluminum. This is important in applications where the coil mass is small compared to the cone mass and mainly low-frequency audio signals are used (e.g., subwoofer). In these cases, the higher density of copper is not relevant but the higher conductivity provides about 3 dB more voltage sensitivity and efficiency (see section 4.1.5 in [3])
Aluminum	Aluminum is more than 3 times lighter than copper. This is important for full-band speakers, tweeters and other applications where the cone mass is small and most of spectral energy is in the passband of the transducer. In these cases, the density is more important than the conductivity and an aluminum coil can generate up to 6dB more voltage sensitivity and efficiency.

6.5 Practical Example

Automotive Speaker	The practical benefits of Green speaker design, such as • 60 % more efficiency, • 5 dB more voltage sensitivity, • Less power consumption and reduced voice coil temperature • 3 dB more SPL output • About 15 dB less harmonic and intermodulation distortion

	have been achieved by reducing the voice coil height in an existing transducer intended for automotive applications as discussed in reference [3].

7 References

7.1 Related Modules	The KLIPPEL RnD System provides a set of simulation tools that can be used to achieve the described optimizing and design tasks. Modules of interest are: • LSIM – simulation of linear transfer behavior of transducers and loud-speaker systems • SIM/SIM2 – nonlinear simulation of transfer behavior of transducers and loudspeaker systems for sinusoidal stimuli • SIM-AUR – nonlinear simulation of transfer behavior of transducers and loudspeaker systems for arbitrary stimuli The following modules may help to assess the suitability of an existing trans-ducer/system for the KCS algorithm and may point out the current limitations of the design. • LPM – identify linear parameters of a transducer • LSI – identify the linear and nonlinear parameters of the transducer • TRF – assessing Rub and Buzz at high displacements • TRF STEP – automation of TRF module with limit checking for Rub and Buzz • TFA – Time Frequency Analysis • SCN/RMA – finding the root cause of rocking modes causing Rub and Buzz • ALS – for finding air leaks and other defects These modules are specific for KCS • KCS-ID Parameter Identification – Manual • KCS Monitor Software – Manual
7.2 Specifications	S72 – KCS Software Library
7.3 Application Notes	AN2 – Separating Spider and Surround AN22 – Rub and Buzz Detection without Golden Unit AN80 – Rocking Mode Analysis

7.4 Publications	[1] W. Klippel, "Loudspeaker and Headphone Design Approaches Enabled by Adaptive Nonlinear Control," J. Audio Eng. Soc., vol. 68, no. 6, pp. 454-464, (2020 June.). doi: https://doi.org/10.17743/jaes.2020.0037 [2] W. Klippel, "Green Speaker Design (Part 1: Optimal Use of System Resources)," presented at the 146th Convention of the Audio Eng. Soc. in Dublin (March 10 2019), paper 10138. Download [3] W. Klippel, "Green Speaker Design (Part 2: Optimal Use of Transducer Resources)," presented at the 146th Convention of the Audio Eng. Soc. in Dublin (March 10 2019), paper 10139. Download [4] W. Klippel, "Mechanical Overload Protection of Loudspeaker Systems," J. Audio Eng. Soc., vol. 64, no. 10, pp. 771 – 783 (October 2016). [5] R. H. Small, "Closed-Box Loudspeaker Systems-Part 1: Analysis," J. Audio Eng. Soc., vol. 20, no. 10, pp. 798-808, (1972 December.). [6] R. H. Small, "Vented-Box Loudspeaker Systems--Part 1: Small-Signal Analysis," J. Audio Eng. Soc., vol. 21, no. 5, pp. 363-372, (1973 June.). [7] RI. H. Small, "Passive-Radiator Loudspeaker Systems Part 1: Analysis," J. Audio Eng. Soc., vol. 22, no. 8, pp. 592-601, (1974 October.). [8] W. Klippel, "Tutorial: Loudspeaker Nonlinearities—Causes, Parameters, Symptoms," J. Audio Eng. Soc., vol. 54, no. 10, pp. 907-939, (2006 October.). [9] Sound System Equipment – Part 21: Acoustical (output based) Measurements, IEC 60268-21:2018. [10] Sound System Equipment – Electro-acoustical Transducers – Measurement of Large Signal Parameters, IEC 62458:2010. [11] Sound System Equipment – Part 22: Electrical and mechanical measurements of transducers, IEC 60268-22:2020.
7.5 Further Resources	Klippel Live Web Seminars – series of webinars covering many aspects of measuring speaker according to IEC60268-21

Find explanations for symbols at:

http://www.klippel.de/know-how/literature.html

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Designs and specifications are subject to change without notice due to modifications or improvements.