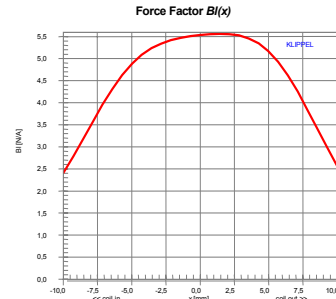


## FEATURES

- Identification of large signal model in real time
- Electrical, mechanical and thermal parameters
- State variables (displacement, temperature,...)
- for woofers in free air, sealed and vented enclosures
- for tweeters, headphones, mini-loudspeakers, shakers
- Measures signal distortion on-line
- Full thermal and mechanical driver protection
- Finds dominant sources of distortion
- Locates weak points in design and assembly



The modules LSI WOOFER, LSI BOX, LSI TWEETER identify the elements of the lumped-parameter model of woofers, tweeters, headphones, shakers, mini-loudspeakers and other electro-dynamical transducers. LSI BOX allows to measure woofers mounted in an enclosure or connected with a horn. The transducer is operated under normal working conditions and excited with an audio-like noise signal. Starting in the small-signal domain the amplitude is gradually increased up to limits admissible for the particular transducer. The maximal amplitude is determined automatically using the identified transducer parameters and general protection parameters describing the thermal and mechanical load.

The identification of the model parameters is performed in real time with an adaptive system. It is based on the estimation of the back EMF from the voltage  $U(t)$  and current signal  $I(t)$  measured at the electrical terminals. The identified model allows locating the sources of the nonlinear distortion and their contribution to the radiated sound. The dynamic generation of a DC-part in the displacement, amplitude compression and other nonlinear effects can be investigated in detail.

After the initial identification a temporal parameter variation and long-term thermal effects can be investigated. The data are stored in the stand-alone processor unit and can be transformed via the USB interface to a connected computer for visualization and interpretation.

Article Numbers:	with DA2 for all SN#	1000-200, 1000-210, 1000-211, 1000-212, 1000-213, 1000-230, 1000-231
Article Numbers:	with DA1 having SN# >140:	1000-220, 1000-221, 1000-221

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updated May 22, 2008

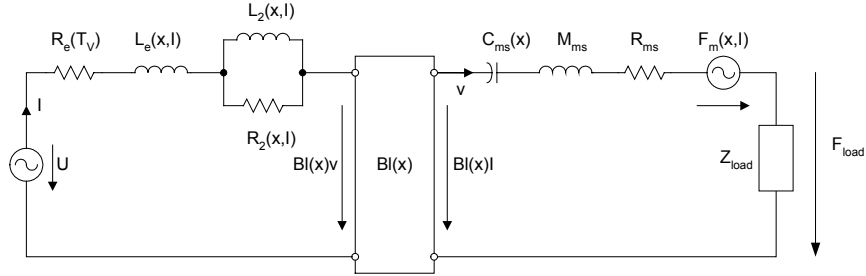


# Large Signal Modeling of the Transducer

**Principle**

The transducers considered here have a moving-coil assembly performing an electro-dynamical conversion of the electrical quantities (current and voltage) into mechanical quantities (velocity and force) and vice versa.

**Equivalent Circuit**

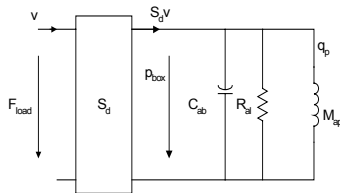


The lumped-parameter model shown above is used to describe the large signal behavior of electro-dynamical drivers at high amplitudes. In contrast to the well known linear model the elements

- electro-dynamical force factor  $Bl(x)$ ,
- compliance of mechanical suspension  $C_{ms}(x)$ ,
- voice coil inductance represented by  $L_e(x, I)$ ,  $L_2(x, I)$  and  $R_2(x, I)$ ,
- resistance of voice coil at DC represented by  $R_e(T_v)$  are not constant parameters but rather depend on one or more speaker states (displacement  $x$ , input current  $I$ , voice coil temperature  $T_v$ )
- additional impedance  $Z_{load}$  represents any additional mechanical or acoustical resonance caused by vented enclosure, panel, horn. For a driver operated in free air the impedance  $Z_{load}=0$ .

For the vented box system the mechanical load  $Z_{load}$  can be represented by the following equivalent circuit.

For the sealed-box system the mechanical load  $Z_{load}$  can be represented by the following equivalent circuit.

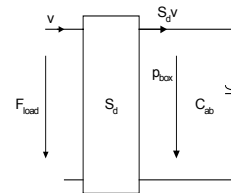


using acoustical compliance  $C_{ab}$

$$C_{ab} = \frac{V_0}{\rho_0 c_0^2}$$

representing the compression of the air volume  $V_0$  with air density  $\rho_0$  and speed of sound  $c_0$ . The Helmholtz resonance and Q factor are defined by

$$f_b = \frac{1}{2\pi} \frac{1}{\sqrt{M_{ap} C_{ab}}} \quad Q_b = \frac{1}{2\pi f_b C_{ab} R_{d1}}$$

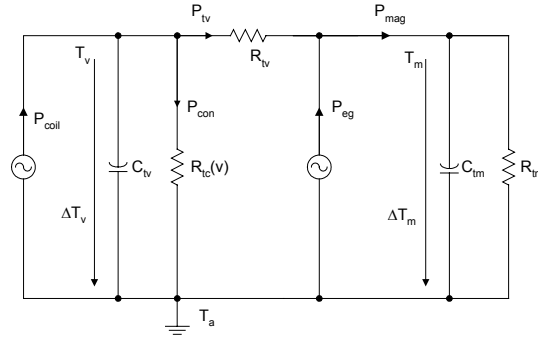


using mechanical compliance  $C_{mb}$

$$\frac{x}{F_{load}} = C_{mb} = \frac{1}{K_{mb}} = \frac{C_{ab}}{S_d^2} = \frac{V_0}{\rho_0 c_0^2 S_d^2}$$

which can be expressed by air volume  $V_0$ , air density  $\rho_0$  and speed of sound  $c_0$ . A total stiffness  $K_{mt}(x)=K_{ms}(x) + K_{mb}$  can be calculated.

**Thermal Modeling**



The heating of the voice coil is modeled by a thermal equivalent circuit comprising two first order integrators connected in series and the thermal resistance

$$R_{tc} = \frac{1}{v_{rms} r_v}$$

due to air convection cooling connected in parallel using the rms-value of the voice coil velocity  $v_{rms}$  and the convection cooling parameter  $r_v$ . The first integrator represents the thermal resistance  $R_{tv}$  (heat transfer between coil and pole tips) and the capacity  $C_{tv}$  (of the coil assembly). The second integrator represents the thermal capacity  $C_{tm}$  (of the frame, magnet, iron path) and the thermal resistance  $R_{tm}$  (heat transfer to the ambience).

using the ambient temperature  $T_a$  and the increase of the voice coil temperature  $\Delta T_v$  and the increase of the magnet temperature  $\Delta T_m$

with the power flowing into the coil

$$P_{coil} = P_{Re} + \alpha P_{eddy} = R_e i^2 + \alpha R_2 (i - i_2)^2$$

using the power dissipated in directly in dc resistance  $R_e$  and a fraction of the power dissipated in  $R_2$  due to eddy currents according to power splitting factor  $\alpha$ . The power

$$P_{eg} = (1 - \alpha) P_{eddy} = (1 - \alpha) R_2 (i - i_2)^2$$

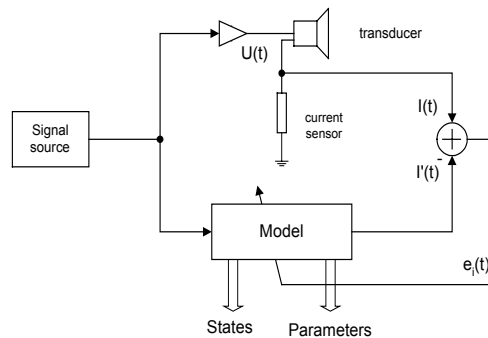
describes the direct heat transfer due to eddy currents in the pole tips which bypasses the coil.

**Operating Condition**

During the Large Signal Identification the transducer has to be operated in free air (LSI WOOFER, LSI TWEETER) or in a sealed or vented enclosure (LSI BOX). It is not recommended to attach an additional mass to the moving assembly because this mass might fall off at higher displacements.

**Identification Technique**

**Principle**



The transducer model is implemented as an adaptive system in a digital signal processor (DSP). The transducer is persistently excited by an audio-like signal generated by a signal source via a power amplifier. The model excited with the voltage  $U(t)$  estimates the voice coil current  $I(t)$  and compares with the measured current  $I(t)$ . The amplitude of the difference signal (error) is minimized by adjusting the model parameters adaptively. The output parameters

are the optimal parameter estimates, the instantaneous state variables (displacement) and statistical values (RMS or peak value, PDF-function, crest factor) which may be investigated. There are three different LSI modules:

- LSI Woofer
- LSI Woofer Box
- LSI Tweeter

which are defined below:

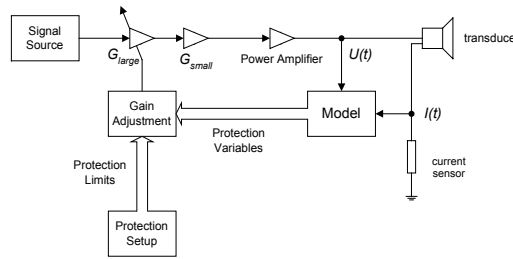
**LSI Woofer**

is dedicated for woofers operated in free air, headphone drivers, shakers and other electro-dynamical transducers where the mechanical-acoustical part can be modeled by a 2<sup>nd</sup>-order system (moving mass, compliance, damping).

<p><b>LSI Woofer BOX</b></p>	<p>allows to measure woofers and other electro-dynamical transducers coupled with an additional mechanical or acoustical resonator (vented enclosure, horn, panel) giving a total mechanical-acoustical system of 2<sup>nd</sup> or 4<sup>th</sup>-order. There are three working modes:</p> <p><u>Free air :</u></p> <p>This mode correspond with the LSI Woofer and assumes that impedance <math>Z_{load}=0</math>.</p> <p><u>Sealed enclosure:</u></p> <p>The stiffness <math>K_{ms}(x)</math> of the mechanical suspension is calculated from the total stiffness <math>K_{mt}(x)</math>. <math>K_{mt}(x)</math> is the sum of the mechanical stiffness <math>K_{ms}(x)</math> and the equivalent stiffness <math>K_{mb}</math> of the enclosed air in the enclosure which is calculated by using the air volume <math>V_b</math> and radiation area <math>S_d</math> of the cone provided by the user.</p> <p><u>Vented enclosure :</u></p> <p>For a vented enclosure the mechanical stiffness <math>K_{ms}(x)</math> of the driver can be separated by considering the imported air volume <math>V_b</math> and radiation area <math>S_d</math>. The port resonance frequency <math>f_b</math> and <math>Q_b</math> factor is determined. This mode may be also used for measuring drive units coupled to an unknown additional resonator (e.g. first break-up mode on a panel) which is assumed to be linear.</p>
<p><b>LSI Tweeter</b></p>	<p>is dedicated for tweeters, horn compression drivers and micro-loudspeakers for telecommunication which may be modeled by a 2<sup>nd</sup>-order mechanical system and a resonance frequency above 400 Hz. It is recommended to perform the measurement in vacuum to suppress nonlinearities of the air flow in small gaps and cavities.</p> <p>NOTE: LSI TWEETER runs only with Distortion Analyzer 2 (DA2) and newer versions of DA 1 (serial number &gt; 140), while LSI WOOFER and LSI BOX work with all DA hardware units.</p>
<p><b>Setup</b></p>	<p>The minimal setup works without computer as a stand-alone system and dispenses with an acoustical or mechanical sensor.</p> <ul style="list-style-type: none"> <li>• Distortion Analyzer</li> <li>• Power amplifier</li> <li>• Amplifier and speaker cable</li> </ul> <p>Usually a personal computer supports interpretation of the results. Optionally a laser displacement sensor may be connected to check the polarity and the orientation of the displacement (coil in and out direction).</p>
<p><b>Import Parameter</b></p>	<p>The minimal setup measures the electrical impedance at the transducer terminals and identifies the electrical system in absolute quantities whereas the mechanical system is identified in relative quantities only. Importing one mechanical parameter (moving mass <math>M_{ms}</math> or <math>Bl(x=0)</math> at the rest position) allows to calibrate all state variables (e.g. the displacement in mm) and all of the mechanical parameters (e.g. compliance in mm/N).</p>
<p><b>Laser – Useful Accessory</b></p>	<div style="display: flex; align-items: center;"> <div style="flex: 1;"> </div> <div style="flex: 1; padding-left: 20px;"> <p>An inexpensive laser sensor based on triangulation principle (see A2 Laser Displacement Sensor) can be used for measuring the voice coil displacement during the test. This information is used to calibrate the mechanical parameters in absolute terms.</p> </div> </div>
<p><b>Adaptation</b></p>	<p>The estimation of the linear, nonlinear and thermal parameters begins with an initial identification performed in a few minutes and goes automatically into a long-term measurement having an arbitrary length (hours, days or even month) determined by the user. The initial identification consist of a series of steps processed sequentially:</p> <ul style="list-style-type: none"> <li>• Amplifier check (cables, gain control, limiting)</li> <li>• Measurement of resistance <math>R_e</math> at DC</li> <li>• Identification of small signal parameters</li> <li>• Identification of admissible amplitude and nonlinear parameters</li> </ul>

• Identification of the thermal parameters

**Protection**



The measurement of the large signal parameters starts in the small signal domain and performs a slow increase of the signal amplitude (enlargement mode) up to the thermal and mechanical limits of the transducer. To avoid an overload or damage a protection system determines the maximal signal amplitude admissible for the particular driver and limits the excitation signal when protection variables (such as voice coil temperature,  $Bl$  or compliance variation) exceed user defined limit values.

**Protection Limits**

The most important setup parameters are the protection limits:

- Maximal increase of voice coil temperature (thermal protection)
- Maximal variation of compliance  $C_{ms}$  versus  $x$  (mechanical protection)
- Maximal variation of force factor  $Bl(x)$  versus  $x$  (excessive motor distortion)
- Maximal input power  $P$  (nominal protection)

In the case that one of the four protection variable exceeds the allowed limit the amplitude of the excitation signal will be reduced.

**Acoustical Environment**

The influence of the room acoustics on the driver parameters may be neglected having a normal room size (volume  $> 30 \text{ m}^3$ ) and keeping a distance of about 1 m to the walls.

**Limits**

**Transducer**

Parameter	Symbol	Min	Typ	Max	Unit
Voice coil resistance @ Speaker 1	$R_e$	0.1	4 - 30		$\Omega$
Voice coil resistance @ Speaker 2	$R_e$	0.2	4- 120		$\Omega$
Resonance frequency for LSI WOOFER, LSI BOX (for LSI TWEETER)	$f_s$	15(100)		400 (4000)	Hz
Total loss factor	$Q_t$	0.3		6	
Voice coil inductance	$L_e$	0.05		5	mH

**Power Amplifier**

Maximal input level				15	dBu
Frequency response ref. 1 KHz @ 5Hz ... 20 kHz				1	dB
Input sensitivity at rated output power			0 (775)		dBu (mV)

**Input Parameters (Setup)**

Parameter	Symbol	Min	Typ	Max	Unit
<b>Protection Limits</b>					
Small signal gain	$G_{small}$	-20		0	dB
Allowed increase of voice coil temperature	$\Delta T_{lim}$	0	60	300	K

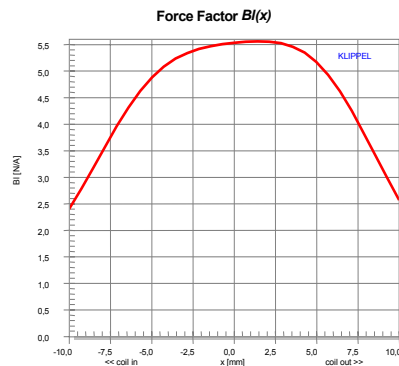
$\Delta T_V$ ,					
Allowed minimal value of the force factor ratio $Bl_{min}$ ,	$Bl_{lim}$	25	50	100	%
Allowed minimal value of the mechanical compliance ratio $C_{min}$ ,	$C_{lim}$	20	50	100	%
Allowed maximal value of electric input power $P$ .	$P_{lim}$	0.01		999	W
<b>Stimulus</b>					
Signal characteristics can be adjusted automatically for the DUT connected.					
Spectral Noise characteristic		pink or white noise			
Cut-off frequency of high pass for LSI WOOFER, LSI BOX (for LSI TWEETER)	$f_{hp}$	10 (40)		150 (1200)	Hz
Cut-off frequency of low pass for LSI WOOFER, LSI BOX (for LSI TWEETER)	$f_{lp}$	200 (400)		1500 (4000)	Hz
<b>Material, Geometry Parameters</b>					
Effective area of the driver diaphragm.	$S_d$	0<		10000	cm <sup>2</sup>
Material of voice coil	copper or aluminum				
<b>Optional Import Parameters</b>					
Voice coil resistance at DC	$R_e(T_V=T_a)$				$\Omega$
Force factor at rest position <sup>1</sup>	$Bl(x=0)$				N/A
Moving mass <sup>1</sup>	$M_{ms}$				kg
Note 1 absolute identification of the mechanical parameters without laser sensor requires import of $Bl(x=0)$ and/or $M_{MS}$					

<b>Measurement Results</b>		LSI Woofer-Driver	LSI Woofer-Box	LSI Tweeter
Article Number:		1000-212	1000-230	1000-220
<b>Parameters at the Rest Position (x=0)</b>				
Electrical parameters $x \ll x_{max}$	$R_e, L_e, L_2, R_2, C_{mes}, L_{ces}, R_{es}$	✓	✓	✓
Mechanical parameters $x \ll x_{max}$	$M_{ms}, R_{ms}, C_{ms}, Bl$	✓	✓	✓
Derived parameters $x \ll x_{max}$	$Q_{eps}, Q_{tp}, Q_{ms}, T_v, Q_{es}, Q_t, f_s, V_{as}, \eta_0, L_m$	✓	✓	✓
Vented box parameters	$Q_p, f_B$		✓	
Electrical signals	$u_{peak}, i_{peak}, u_{rms}, i_{rms}, P$	✓	✓	✓
Displacement	$x_{peak}, x_{bottom}, x_{dc}, x_{prot}$	✓	✓	✓
Analyzed distortion components	$d_c, d_L, d_{Bl}$	✓	✓	✓
Temperature, power compression	$\Delta T_V, PC$	✓	✓	✓
Nonlinear Parameter Variation	$B_{min}, C_{min}, L_{min}$	✓	✓	✓
<b>Nonlinear Parameters</b>				
Displacement varying Inductance	$L_e(x), L_e(x_{rel})$	✓	✓	✓
Current varying Inductance ("flux modulation")	$L_e(i)$	✓	✓	
Force factor (Bl-product)	$Bl(x), Bl(x_{rel})/Bl(0)$ ,	✓	✓	✓
Suspension characteristic	$K_{ms}(x), C_{ms}(x), C_{ms}(x_{rel})/C_{ms}(0)$	✓	✓	✓
Electrical parameters	$C_{mes}(x), L_{ces}(x), R_{es}(x), C_{mes}(x_{rel}), L_{ces}(x_{rel}), R_{es}(x_{rel})$	✓	✓	✓

Coefficients of power series for $Bl(x)$ , $C_{ms}(x)$ , $L(x)$	up to 8 <sup>th</sup> order	✓	✓	✓
Derived parameters	$Q_{eps}(x, T_v)$ , $Q_{tp}(x, T_v)$ , $Q_{ms}(x, T_v)$ , $Q_{es}(T_v)$ , $Q_t(x, T_v)$ , $f_s(x)$ , $P_{Re}$ , $P_{con}$	✓	✓	✓
Optimal voice coil shift	$x_{BI}(x)$	✓	✓	✓
Optimal suspension shift	$x_C(x)$	✓	✓	✓
Total Stiffness (suspension + air) in sealed enclosure	$K_{mt}(x)$		✓	
<b>Thermal Parameters</b>				
Thermal resistance	$R_{tv}$ , $R_{tm}$ , $r_V$	✓	✓	✓
Thermal capacity	$C_{tv}$ , $C_{tm}$ , $\tau_{tm}$ , $\tau_{tv}$	✓	✓	✓
Convection Cooling	$r_V$	✓	✓	✓
Heating by eddy currents	$\alpha$	✓	✓	✓
<b>History</b>				
Parameter and state variation versus measurement time t		✓	✓	✓
Background monitoring at high sample rate (Death Report)		✓	✓	✓
<b>Export</b>				
Result windows to report generator		✓	✓	✓
Graphics to Clipboard, File (various formats)		✓	✓	✓
Parameters for Auralization		✓	✓	✓
Parameters for Simulation		✓	✓	✓

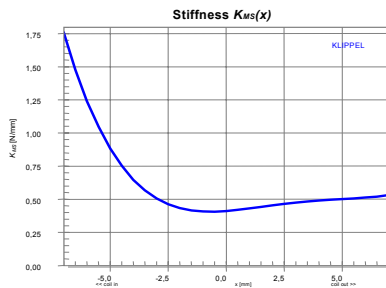
### Transducer Nonlinearities

#### Force Factor (BI-product)



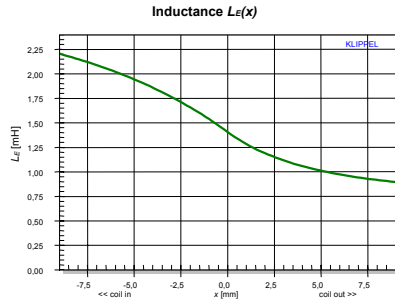
The force factor  $Bl(x)$  describes the integral of the induction  $B$  versus wire length  $l$  depending on the instantaneous coil position  $x$  in the gap. The  $Bl(x)$  curve comprises a symmetrical and an asymmetrical component and vanishes for high displacements. The asymmetry may be caused by the field geometry or by an offset of the coil. Variation of  $Bl(x)$  versus  $x$  affects the parametric excitation of the driver (varying driving force) and the electrical damping at the resonance (loss factor  $Q_{es}$  is not constant).

#### Stiffness of Mechanical Suspension



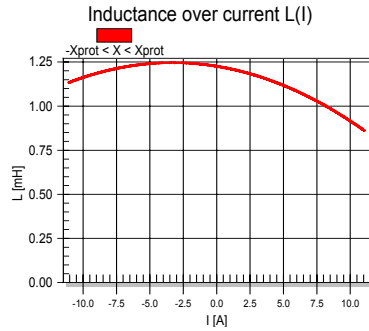
The stiffness  $K_{ms}(x)$  which is the inverse of the compliance  $C_{ms}(x)$  describes the ratio of the instantaneous force and displacement at the working point  $x$ . A high increase of the stiffness indicates the limit of the moving capability of the mechanical suspension. Variation of  $K_{ms}(x)$  corresponds with instantaneous variation of the resonance frequency  $f_s(x)$  and the mechanical loss factor  $Q_{ms}(x)$  versus displacement.

**Voice Coil Inductance versus displacement**



The parameters representing the voice coil inductance  $L_e(x)$ ,  $L_2(x)$  and  $R_2(x)$  have the same nonlinear characteristic. Transducers without any additional means for reducing the inductance (short cut ring) have an asymmetrical shape giving maximal inductance when the coil is below the plate. Variation of the inductance parameters will vary the electrical impedance and produce a reluctance force on the mechanical side which may be interpreted as an additional electromagnetic driving mechanism.

**Voice Coil Inductance versus current**



The nonlinear  $B(H)$  characteristic of the iron causes a variation of the inductance  $L(i)$  versus voice coil current  $i$ . This nonlinearity is also called flux modulation or better permeability modulation. An symmetric characteristic shows a saturation of the iron at high positive and negative current. The curve becomes asymmetric for a high DC flux generated by the magnet. The parameter  $L(i)$  causes harmonic distortion at higher frequencies which can easily be detected in the input current.

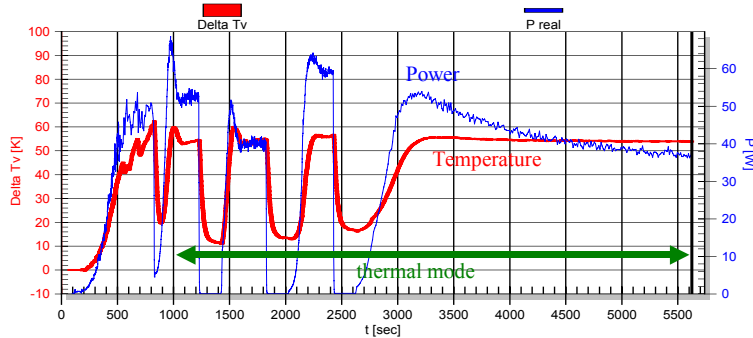
**Temporal Variations of States and Parameters**

**Permanent Monitoring**

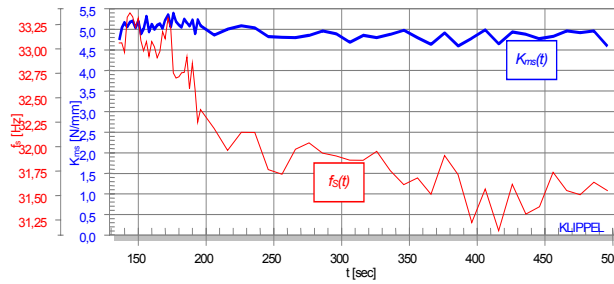
During the identification process all of the parameter estimates and important characteristics of the state variables (peak and rms values) are sampled periodically (about 2 –10 s) and stored in a buffer within the Distortion Analyzer. Connecting a computer via USB interface makes it possible to view the complete history of the measurement and to investigate temporal variations of the parameters due to thermal, reversible and irreversible processes.

**Temperature, power**

The voice coil temperature, the real input power  $P_{real}$  and the power  $P_{Re}$  dissipated on resistance  $R_e$  is permanently measured and recorded. This information is helpful to protect the driver against overload but is also used to identify the thermal parameters. During the thermal identification which takes about 1 hour the loudspeaker is excited by different noise signal interrupted by cooling procedure to measure the convection cooling and the heating of the poles by eddy currents.

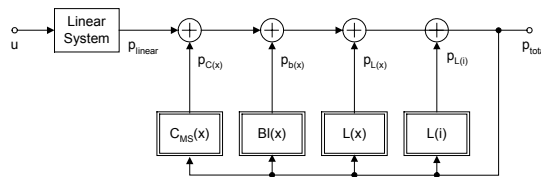


**Stiffness of Mechanical Suspension**



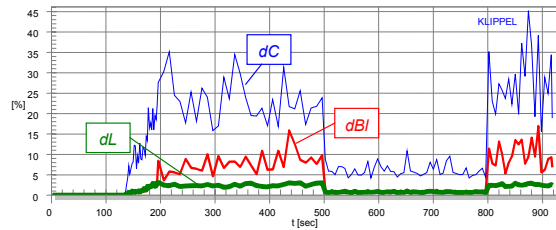
The properties of the mechanical suspension vary with time due to reversible and nonreversible processes (creep, ageing).

**Distortion Analysis**



The transducer may be modeled as a superposition of a linear system excited by the input signal and the outputs of nonlinear subsystems corresponding to the driver nonlinearities  $BI(x)$ ,  $C_{ms}(s)$  and  $L_e(x)$  and  $L_e(i)$ .

The digital model implemented in the DSP makes it possible to measure the peak values of the outputs  $p_{C(x)}(t)$ ,  $p_{BI(x)}(t)$ ,  $p_{L(i)}(t)$  and  $p_{L(x)}(t)$  of the nonlinear subsystems separately and to refer this to the peak value of the total output  $p_{total}$ . This ratios are called instantaneous distortions  $d_C$ ,  $d_{BI}$ ,  $d_L$  and  $d_{L(i)}$  show the contribution from each nonlinearity versus measurement time.

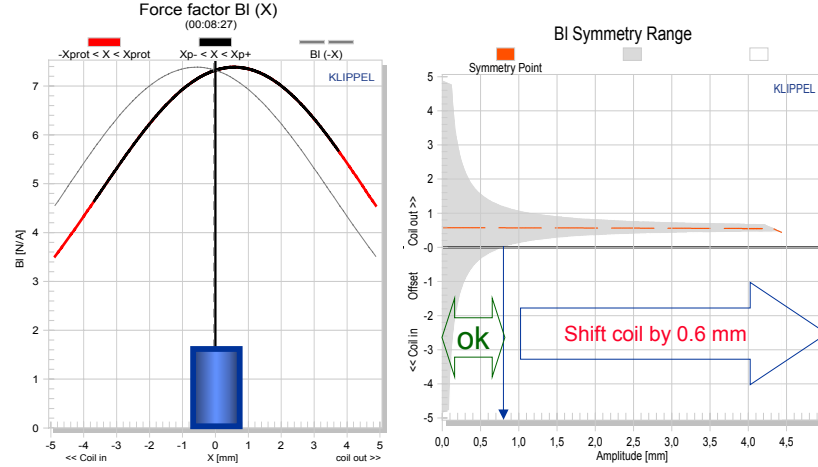


This kind of Distortion Analysis shows the dominant source of distortion.

# Applications / Diagnostics

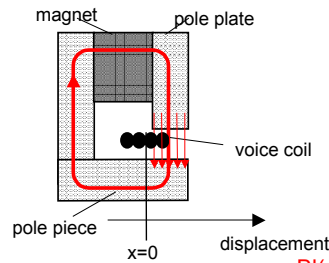
## Finding the optimal rest position of the Voice Coil

The force factor characteristic  $Bl(x)$  and the corresponding diagram showing the  $Bl$  symmetry point versus Amplitude show the optimal rest position of the voice coil

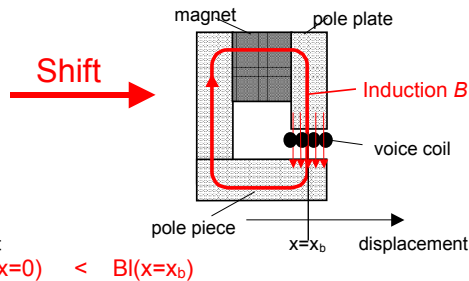


If the symmetry point  $x_B(x)$  is independent of the displacement amplitude  $x$  (dashed red curve in the upper right diagram) then the force factor asymmetry is caused by an offset of the voice coil position and can be simply compensated by shifting the voice coil rest position (0.6 mm in the upper example). If the loudspeaker is only operated at small amplitudes only (smaller than 0.8 mm in the example above) then the voice coil offset produces less than 5 % variation of the  $Bl$  factor ( $x=0$  curve is still in the grey symmetry range).

Starting point:

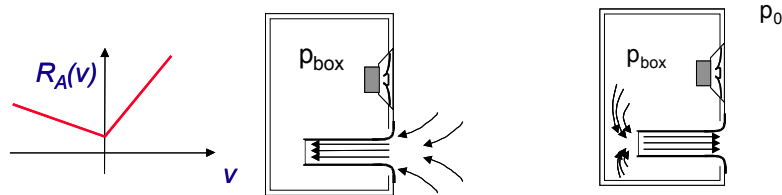


Result:



## DC offset generated by asymmetrical port geometry

An asymmetrical shape of the port may cause a rectification of the air flow in vented enclosures. The generation of a pressure difference at the port's orifices may generate a significant dynamic shift of the rest position of the coil.

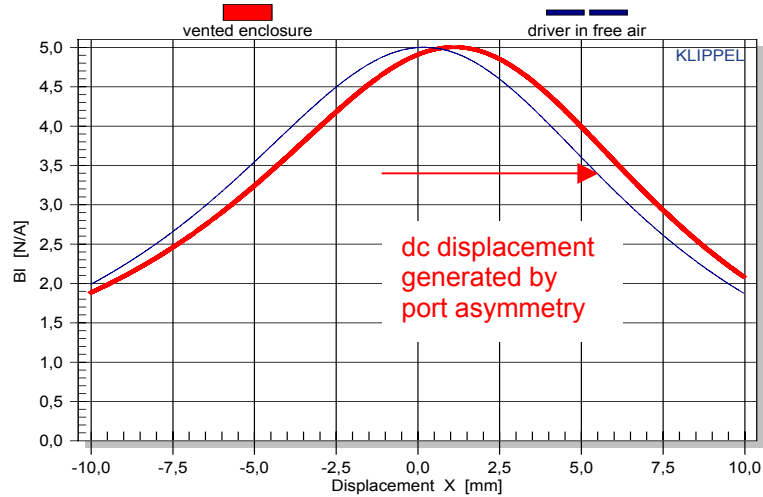


This problem can be detected by two measurements using the LSI Woofer box.

Step 1: Measure the driver in free air by using the free air measurement mode of the LSI woofer box. Determine the rest position of the coil.

Step 2: Mount the same driver in a vented enclosure and perform a measurement in the mode vented enclosure. Check the shift of the voice coil position.

Force factor BI vs. displacement X



Find explanations for symbols at <http://www.docs.klippel.de/symbols.pdf>



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updated May 22, 2008

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