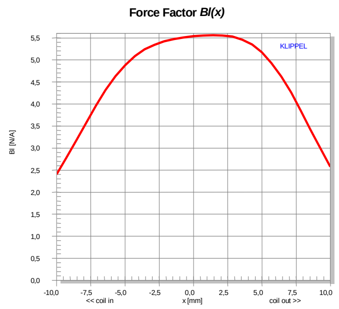
Large Signal Identification (LSI) S1

Module of the R&D SYSTEM

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:	1000-212, 1000-213, 1000-230, 1000-231,1000-232, 1000-220,1000-221

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KLIPPEL

Klippel GmbH
Mendelssohnallee 30
01309 Dresden, Germany

www.klippel.de
info@klippel.de

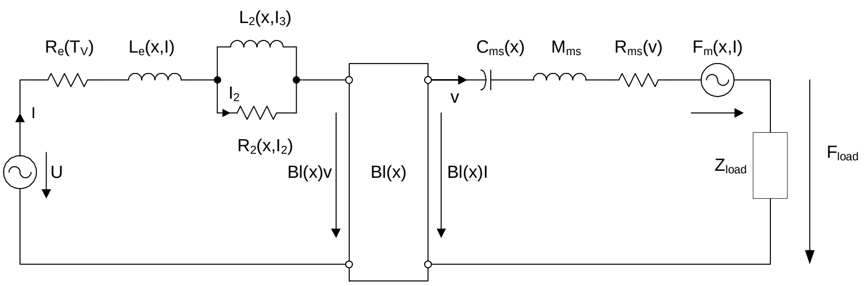
TEL: +49-351-251 35 35
FAX: +49-351-251 34 31

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.

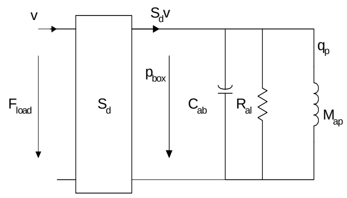
Equivalent Circuit



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 $R_2(x,I)$,
- mechanical losses $R_{ms}(v)$
- 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.



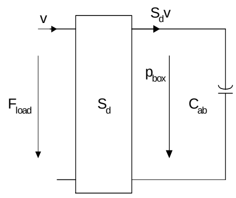
using acoustical compliance C_{ab}

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

representing the compression of the air volume V_0 with air density ρ_0 and speed of sound c_0. The Helmholtz resonance and Q factor are defined by

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

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



using mechanical compliance C_{mb}

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

which can be expressed by air volume V_0, air density ρ_0 and speed of sound c_0.
A total stiffness $K_{mt}(x)=K_{ms}(x) + K_{mb}$ can be calculated.

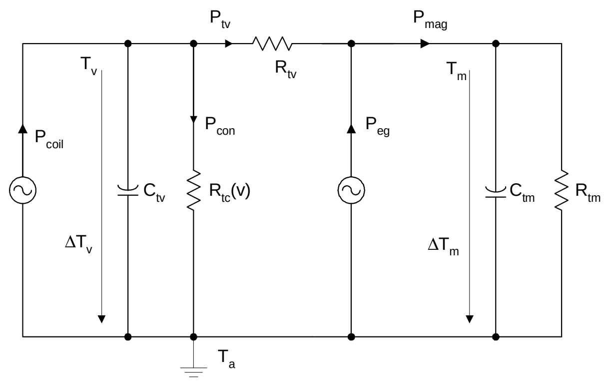
Thermal Modeling

The heating of the voice coil is modeled by a thermal equivalent circuit comprising two first order integrators connected in series describing the increase of the voice coil temperature ΔT_v and the increase of the magnet temperature ΔT_m referred to the ambient temperature T_a. The first integrator corresponds with 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).

The thermal resistance

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

represents air convection cooling and depends on the rms-value of the voice coil velocity v_{rms} and the convection cooling parameter r_V.



The power

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

heats up the coil directly and consist of the power P_{Re} dissipated in dc resistance R_e and a fraction of the power P_{eddy} dissipated in R_2 due to eddy currents weighted by power splitting factor α. The power

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

describes the remaining part of P_{eddy} which is directly be transferred to the pole tips and bypasses the coil.

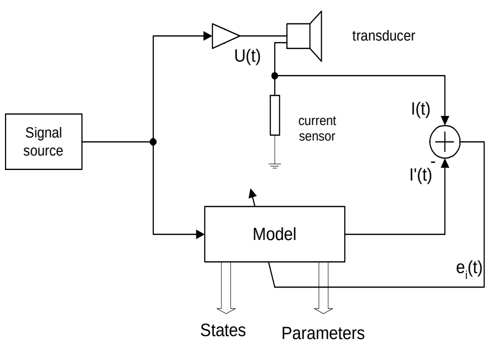
Please find more information in the paper: W. Klippel, "Nonlinear Modeling of the Heat Transfer in Loudspeakers," J. Audio Eng. Soc. Vol. 52, No ½ 2004 January, February.

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^{nd}-order system (moving mass, compliance, damping).

LSI Woofer BOX

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 2nd or 4th-order. There are three working modes:

Free air :

This mode correspond with the LSI Woofer and assumes that impedance Z_{load}=0.

Sealed enclosure:

The stiffness Kms(x) of the mechanical suspension is calculated from the total stiffness K_{mt}(x). K_{mt}(x) is the sum of the mechanical stiffness K_{ms}(x) and the equivalent stiffness K_{mb} of the enclosed air in the enclosure which is calculated by using the air volume V_b and radiation area S_d of the cone provided by the user.

Vented enclosure :

For a vented enclosure the mechanical stiffness K_{ms}(x) of the driver can be separated by considering the imported air volume V_b and radiation area S_d. The port resonance frequency f_b and Q_b 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.

LSI Tweeter

is dedicated for tweeters, horn compression drivers and micro-loudspeakers for telecommunication which may be modeled by a 2nd-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.

NOTE: LSI TWEETER runs only with Distortion Analyzer 2 (DA2) and newer versions of DA 1 (serial number > 140), while LSI WOOFER and LSI BOX work with all DA hardware units.

Setup

The minimal setup works without computer as a stand-alone system and dispenses with an acoustical or mechanical sensor.

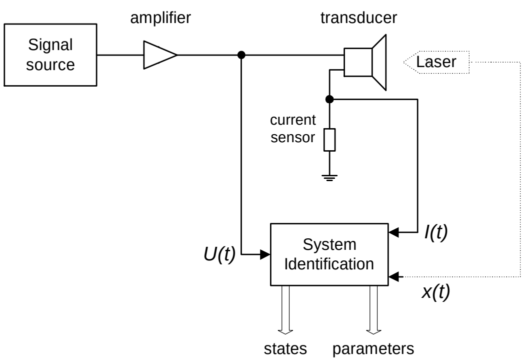
- Distortion Analyzer
- Power amplifier
- Amplifier and speaker cable

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).

Import Parameter

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 M_{ms} or *Bl(x=0)* 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).

Laser – Useful Accessory



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.

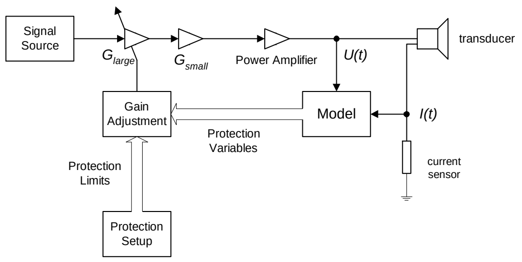
Adaptation

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:

- Amplifier check (cables, gain control, limiting)
- Measurement of resistance R_e at DC
- Identification of small signal parameters
- Identification of admissible amplitude and nonlinear parameters

- 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 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		Ω
Voice coil resistance @ Speaker 2	R_e	0.2	4- 120		Ω
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)
Signal processing latency @ LSI Woofer				12.1	ms
Signal processing latency @ LSI Tweeter				6.2	ms

Input Parameters (Setup)

Parameter	Symbol	Min	Typ	Max	Unit

Protection Limits					
Small signal gain	G_{small}	-20		0	dB
Allowed increase of voice coil temperature ΔT_V,	ΔT_{lim}	0	60	300	K
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
Stimulus 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
Material, Geometry Parameters					
Effective area of the driver diaphragm.	S_d	0<		10000	cm^2
Material of voice coil	copper or aluminum				
Optional Import Parameters					
Voice coil resistance at DC	$R_e(T_v=T_a)$				Ω
Force factor at rest position[1]	$Bl(x=0)$				N/A
Moving mass[1]	M_{ms}				kg
Note 1 absolute identification of the mechanical parameters without laser sensor requires import of $Bl(x=0)$ and/or M_{MS}					

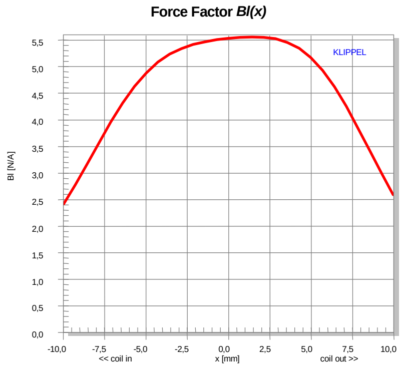
Measurement Results		LSI Woofer-Driver	LSI Woofer-Box	LSI Tweeter
Article Number:		1000-212	1000-230	1000-220
Parameters at the Rest Position (x=0)				
Electrical parameters $x<<x_{max}$	R_e, L_e, L_2, R_2, C_{mes}, L_{ces}, R_{es}	✓	✓	✓
Mechanical parameters $x<<x_{max}$	M_{ms}, R_{ms}, C_{ms}, Bl	✓	✓	✓
Derived parameters $x<<x_{max}$	Q_{eps}, Q_{tp}, Q_{ms}, T_v, Q_{es}, Q_t, f_S, V_{as}, η_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	ΔT_v, PC	✓	✓	✓
Nonlinear Parameter Variation	B_{min}, C_{min}, L_{min}	✓	✓	✓
Nonlinear Parameters				
Displacement varying Inductance	$L_e(x)$, $L_e(x_{rel})$	✓	✓	✓
Current varying Inductance (“flux modulation”)	$L_e(i)$	✓	✓	
Mechanical losses	$R_{ms}(v)$			✓

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 8th 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	$x_{Bl}(x)$	✓	✓	✓
Optimal suspension shift	$x_C(x)$	✓	✓	✓
Total Stiffness (suspension + air) in sealed enclosure	$K_{mt}(x)$		✓	
Thermal Parameters				
Thermal resistance	R_{tv}, R_{tm}, r_V	✓	✓	✓
Thermal capacity	C_{tv}, C_{tm}, τ_{tm}, τ_{tv}	✓	✓	✓
Convection Cooling	r_v,	✓	✓	✓
Heating by eddy currents	α	✓	✓	✓
History				
Parameter and state variation versus measurement time t		✓	✓	✓
Background monitoring at high sample rate (Death Report)		✓	✓	✓
Export				
Result windows to report generator		✓	✓	✓
Graphics to Clipboard, File (various formats)		✓	✓	✓
Parameters for Auralization		✓	✓	✓
Parameters for Simulation		✓	✓	✓

Transducer Nonlinearities

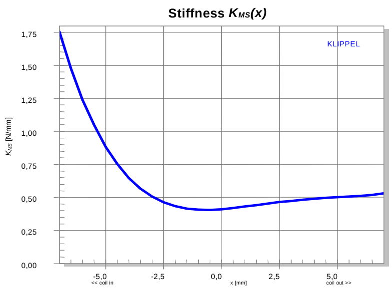
Force Factor

(Bl-product)



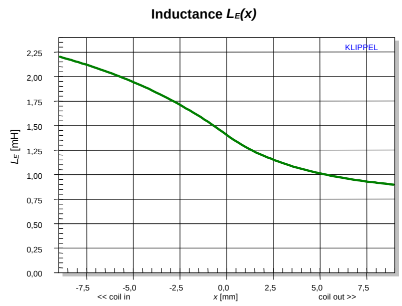
The force factor $Bl(x)$ describes the integral of the induction B versus wire length l depending on the instantaneous coil position x in the gap. The $Bl(x)$ curve comprises a symmetrical and an asymmetrical component and vanishes for high displacements. The asymmetry may be caused by the field geometry 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



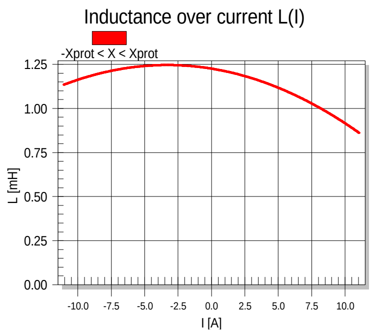
The stiffness $K_{ms}(x)$ which is the inverse of the compliance $C_{ms}(x)$ describes the ratio of the instantaneous force and displacement at the working point x. A high increase of the stiffness indicates the limit of the moving capability of the mechanical suspension. Variation of $K_{ms}(x)$ corresponds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

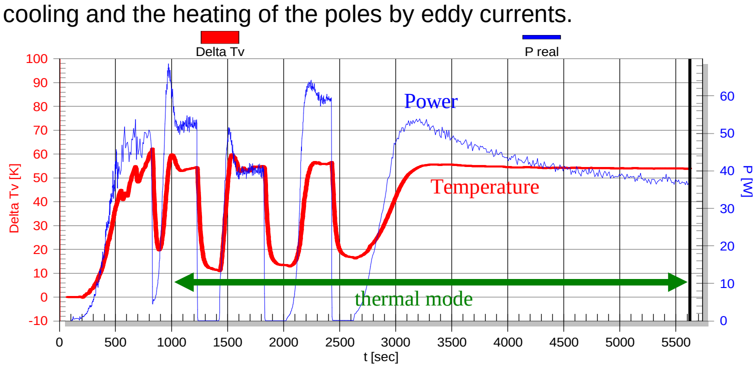
Temporal Variations of States and Parameters

Permanent Monitoring

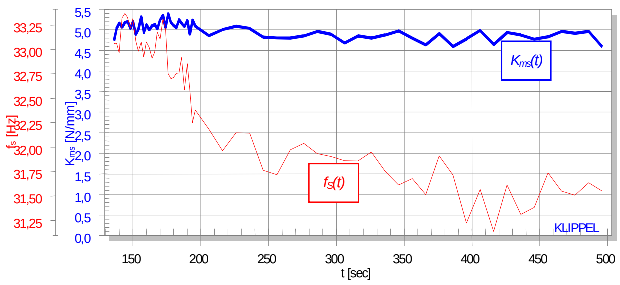
During the identification process all of the parameter estimates and important characteristics of the state variables (peak and rms values) are sampled periodically (about 2 –10 s) and stored in a buffer within the Distortion Analyzer. Connecting a computer via USB interface makes it possible to view 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.

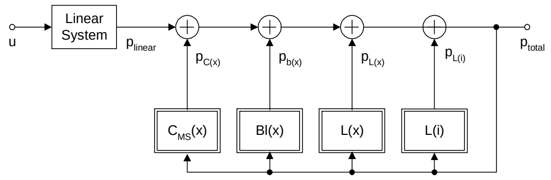


Stiffness of Mechanical Suspension



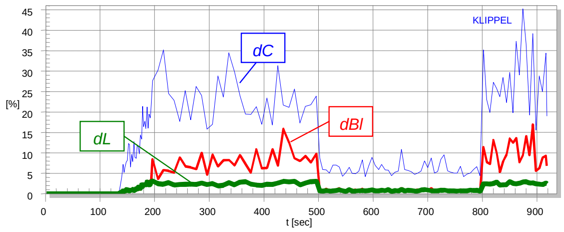
The properties of the mechanical suspension vary with time due to reversible and nonreversible processes (creep, ageing).

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 *Bl(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 $p_{C(x)}(t)$, $p_{Bl(x)}(t)$, $p_{L(i)}(t)$ 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_{Bl}, d_L and $d_{L(i)}$ show the contribution from each nonlinearity versus measurement time.

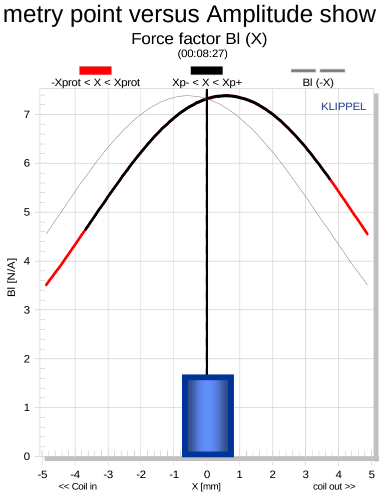


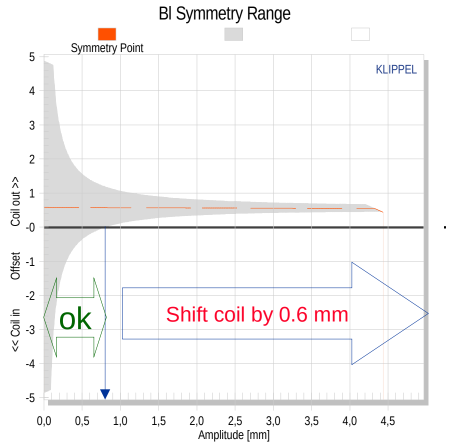
This kind of Distortion Analysis shows the dominant source of distortion.

Applications / Diagnostics

Finding the optimal rest position of the Voice Coil

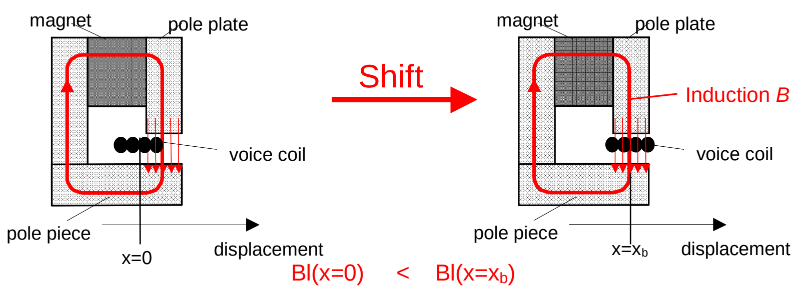
The force factor characteristic Bl(x) and the corresponding diagram showing the Bl symmetry point versus Amplitude show the optimal rest position of the voice coil





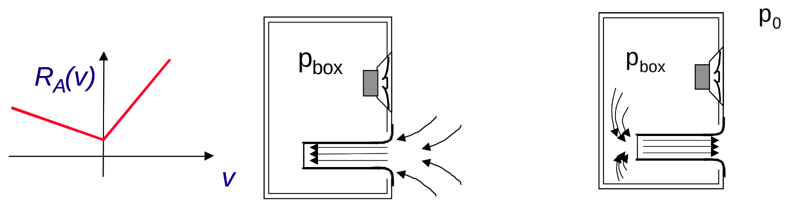
If the symmetry point $x_B(x)$ is independent of the displacement amplitude x (dashed red curve in the upper right diagram) then the force factor asymmetry is caused by an offset of the voice coil position and can be simply compensated by shifting the voice coil rest position (0.6 mm in the upper example). 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

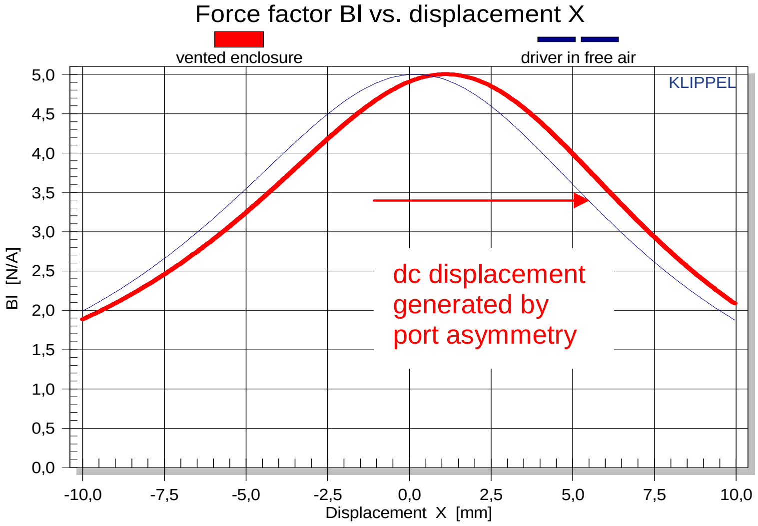
An asymmetrical shape of the port may cause a rectification of the air flow in vented enclosures. The generation of a pressure difference at the port's orifices may generate a significant dynamic shift of the rest position of the coil.



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.



Find explanations for symbols at http://www.klippel.de/know-how/literature.html

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Klippel GmbH
Mendelssohnallee 30
01309 Dresden, Germany

www.klippel.de
info@klippel.de

TEL: +49-351-251 35 35
FAX: +49-351-251 34 31