Hands-On Training 3

Loudspeaker Nonlinearities

1 Objectives of the Hands-on Training

- Identifying the physical cause of nonlinear distortion generated by loudspeakers
- Modeling the transducer by using nonlinear lumped parameters
- Understanding the relationship between constructional design topologies and loudspeaker nonlinearities
- Performing dynamic measurement of loudspeaker nonlinearities
- Developing practical skills in interpreting nonlinear parameters
- Avoiding common mistakes in measurements

2 Requirements

2.1 Previous Knowledge of the Participants

We recommend completion of *Klippel Trainings* 1 and 2 before starting this training.

2.2 Minimum Requirements

Participants will need the results of the measurement provided in a Klippel database ***Loudspeaker Nonlinearities.kdbx*** dispensing with a complete setup of the KLIPPEL measurement hardware. The data may be viewed by downloading *dB-Lab* from www.klippel.de/training and installing the software on a Windows PC.

2.3 Optional Requirements

If participants have access to a KLIPPEL R&D Measurement System, we recommend performing additional measurements on transducers, provided by the instructor or other participants. In order to perform these measurements, you will also need the following software and hardware components:

- Large Signal Identification Module (LSI)
- Distortion Analyzer DA2
- Laser Sensor + Controller
- Amplifier
- Driver Stand

3 The Training Process

1. Review the theory that follows to refresh knowledge required for the training.
2. Watch the demo video to learn about the practical aspects of the measurement.
3. Answer the preparatory questions to check your understanding.
4. Follow the instructions to interpret the results in the database and answer the multiple-choice questions off-line.
5. Check your knowledge by submitting your responses to the anonymous evaluation system at http://www.klippel.de/.
6. Receive an email containing a **Certificate of Mastery, Knowledge or Participation** (depending on your performance).
7. Perform optional measurements on transducers if the hardware is available.

4 Introduction

Loudspeakers sound different in the small and large signal domains. Nonlinearities inherent in the loudspeaker generate additional signal distortion at higher amplitudes. These nonlinearities are directly related to the transducer's limited resources, such as size and weight of the magnet, height of the voice coil compared with depth of the gap and other geometrical properties of the suspension system. Thus the lumped parameters (e.g. force factor *Bl*) of the electro-acoustical equivalent circuit as introduced in the first hands-on training are not constants, but depend on instantaneous state variables (e.g. voice coil displacement *x*). The variation of the lumped parameters, corresponding with the nonlinear curve shape, generates nonlinear signal distortion comprising new spectral signal components. These are known as harmonics and intermodulation, and are not found in the input signal supplied to the loudspeaker.

While a linear model can explain the loudspeaker behavior at small amplitudes, a nonlinear model is required to investigate:

- Factors limiting the acoustical output (especially at low frequencies)
- Generation of audible distortion (having a high impact on sound quality)
- Overload situation (causing fatigue and damage)
- Unstable behavior (generating bifurcation and dynamic voice coil offset)
- Optimal design (performance-cost ratio at low weight and size)
- Efficiency of the transducer (important for battery life in portable audio devices)
- Self-protection of the speaker (soft limiting of the voice coil displacement)

The following theoretical section provides a short overview of loudspeaker modeling in the large signal domain, which is required for the hands-on trainings that follows.

4.1 Important Transducer Nonlinearities

The most dominant regular nonlinearities found in an electro-dynamic loudspeaker will be discussed in the following sections.

4.1.1 Stiffness $K_{ms}(x)$

The Stiffness $K_{ms}(x)$ describes the nonlinear relationship between the restoring force $F = K_{ms}(x)x$ of the loudspeaker suspension system and the voice coil displacement x. At small amplitudes the stiffness is almost constant. At higher amplitudes, the stiffness rises significantly with displacement generating a high value of the restoring force when the suspension material is stretched and the geometry of the corrugation rolls is significantly deformed (see Figure 1). The nonlinear compliance $C_{ms}(x) = 1 / K_{ms}(x)$ stiffness is the inverse of the nonlinear stiffness.

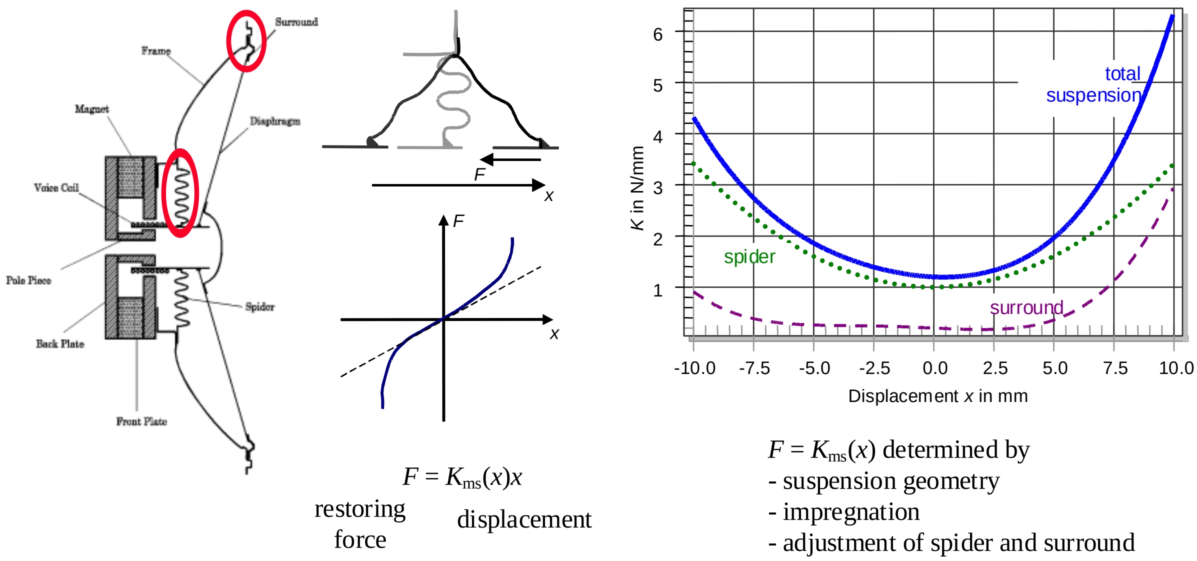


Figure 1: Surround and spider as the main cause of the nonlinear stiffness $K_{ms}(x)$

4.1.2 Force Factor *Bl*(*x*)

The force factor *Bl*(*x*) describes the coupling between the electrical and mechanical domain of an electro-dynamic transducer, and is defined as the integral value of the magnetic flux density *B* over the voice coil length *l*. The force factor *Bl*(*x*) is not constant as assumed in linear loudspeaker modeling, but is a function of voice coil displacement *x* in real transducers. The force factor *Bl*(*x*) decreases for high positive and negative displacement when more and more windings of the coil leave the gap where the magnetic flux density *B* is high. For most applications, a symmetrical shape of *Bl*(*x*) is desired, which shows its maximum at the voice coil rest position *x* = 0 (see Figure 2).

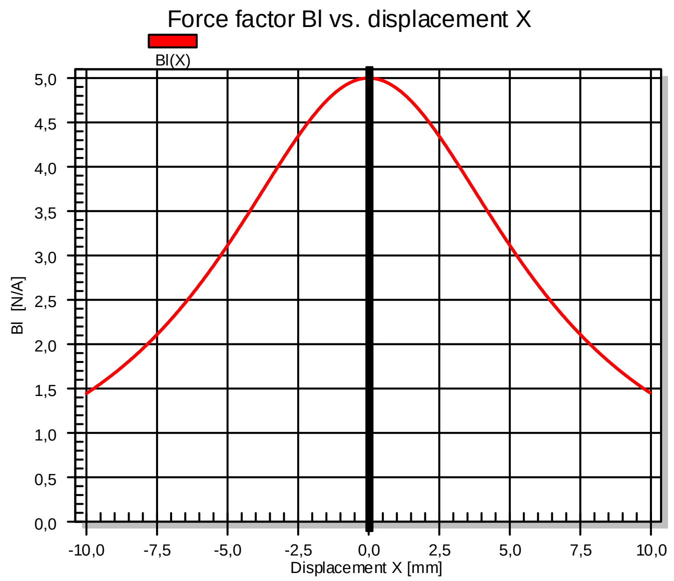


Figure 2: Force factor *Bl*(*x*) versus voice coil displacement *x*

The force factor *Bl*(*x*) has two nonlinear effects in the electro-dynamical transducer:

- The force $F=Bl(x)i$ exciting the mechanical system and depending on the voice coil position *x* generates a nonlinear interaction between voice coil current *i* and displacement *x*.
- A voltage (Electro Motive Force EMF) $u_{EMF}=Bl(x)v$ (back) is generated on the electrical side of the electro-dynamical transducer and produces a nonlinear interaction between displacement *x* and velocity *v*.

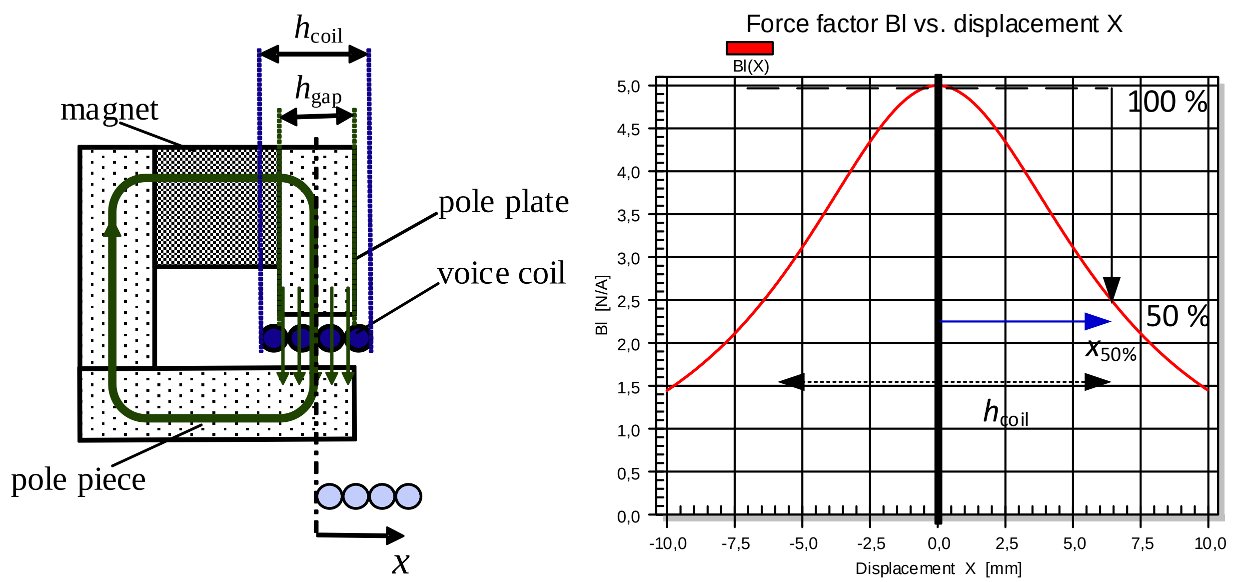


Figure 3: Nonlinear force factor characteristic *Bl*(*x*) of an equal-length configuration

There is a direct relationship between the motor topology (voice coil height and gap depth) and the curve shape of the force factor *Bl*(*x*) versus displacement. The equal-length configuration as shown in Figure 3 provides the highest Bl-value at the rest position but early decay of the curve. The overhang configuration, as shown in Figure 4, generates a plateau region in the *Bl*(*x*)-curve because the number of windings inside the gap is constant for small displacement of the coil. Neglecting the fringe field outside the magnetic gap the voice coil displacement $x_{50\%}$ where the force factor decreases to 50 % corresponds with the height h_{coil} of the voice coil in both topologies.

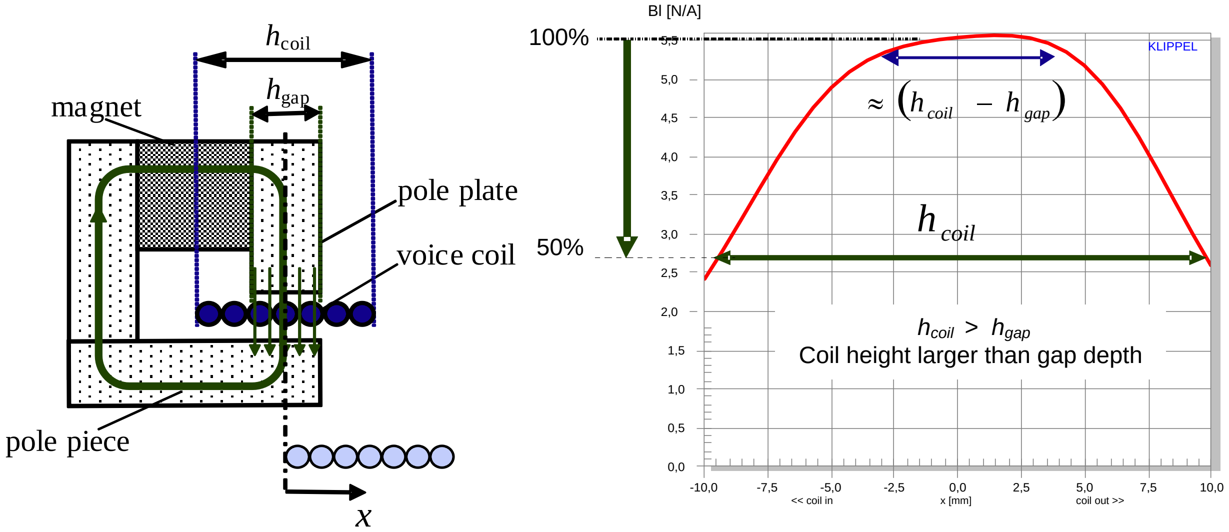


Figure 4: Nonlinear force factor characteristic *Bl(x)* of an overhang characteristic

4.1.3 Voice Coil Inductance $L_e(x, i = 0)$

The inductance of the voice coil L_e is also an important nonlinearity in woofers and subwoofers because electrical current produces a magnetic AC-field which depends on the position *x* of the coil.
If the coil is moved to positive direction the windings generate a much lower magnetic flux Φ in free air than operating the coil at negative displacement where the coil is surrounded by iron. This nonlinearity can be reduced by conductive material such as shorting rings or caps made of aluminum or copper located close to the coil as shown in Figure 5. This generates a counter flux $\Phi_{counter}$ which reduces the total flux at negative displacement.

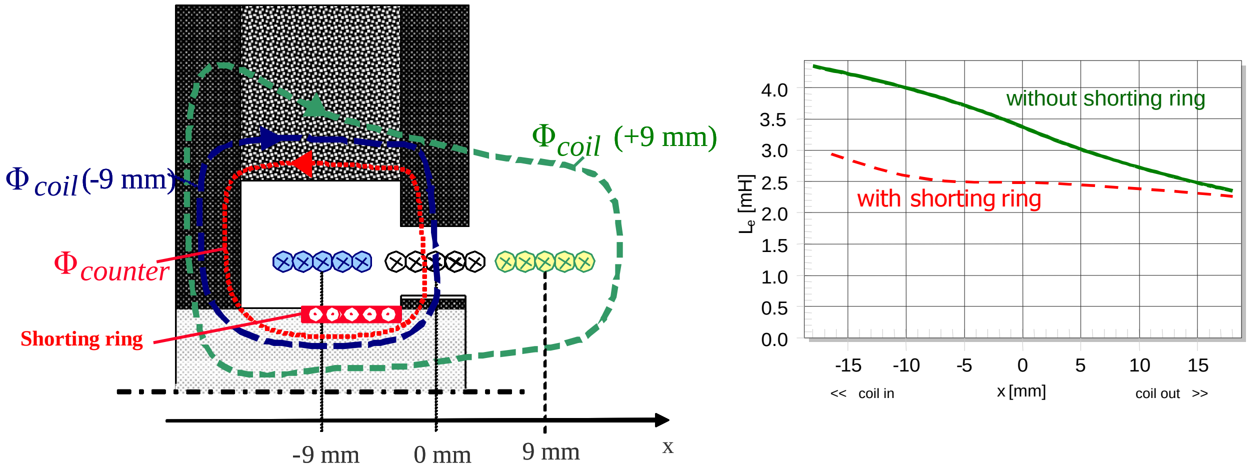
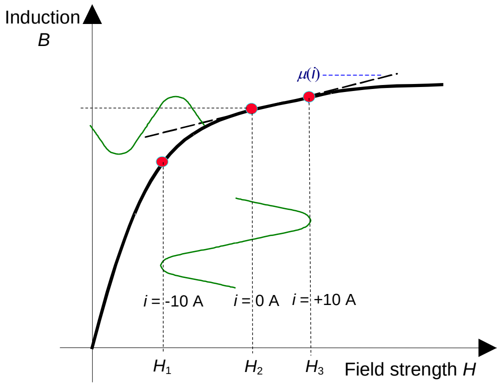


Figure 5: Placing the shorting ring below the gap reduces the voice coil inductance $L_e(x, i = 0)$ for negative displacement and provides an almost constant inductance.

4.1.4 Voice Coil Inductance $L_e(i, x = 0)$

The inductance $L_e(i)$ of the coil also depends on the electrical current i because there is a nonlinear relationship between magnetic field strength H and flux density B (induction) in the iron material. Figure 6 shows the variation of the total flux density at displacement $x = 0$ for three different values of the voice coil current. For $i = 0$ A, the magnet produces the field strength H_2 which determines the working point in the $B(H)$-characteristic. A high positive current ($i = 10$ A) increases the total field strength H_3 and operates the iron at higher saturation where the permeability μ is decreased. The variation of the permeability $\mu(i)$ causes a dependency of the inductance $L_e(x, i)$ on current $\underline{i}$.



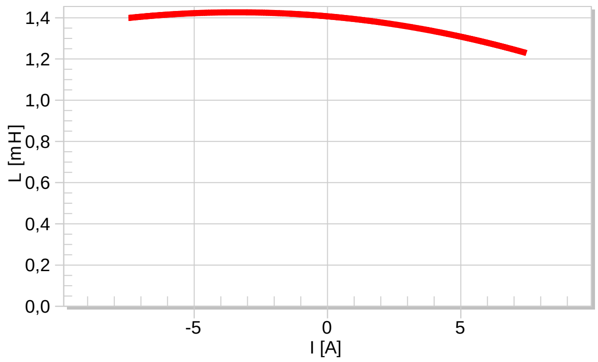


Figure 6: Voice coil inductance $L_e(i, x = 0)$ versus voice coil current $\underline{i}$

Nonlinear inductance $L_e(i, x = 0)$ may be reduced by using short coils, an optimal designed iron path or placing shorting material close to the coil.

4.2 Nonlinear Lumped Parameter Model

The interaction between the dominant loudspeaker nonlinearities can be investigated by establishing a lumped parameter model as shown in Figure 7.

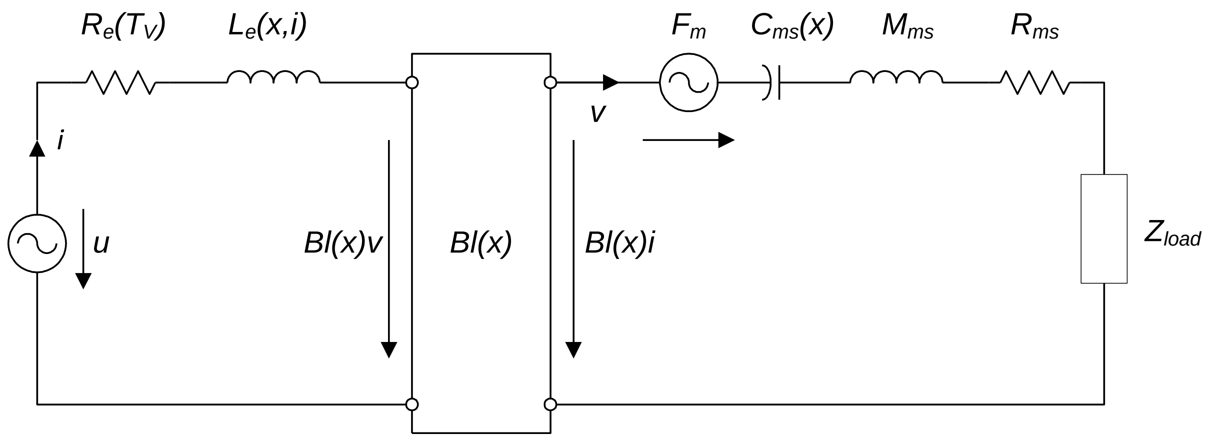


Figure 7: Equivalent circuit of the electro-dynamical transducer considering nonlinear lumped parameters

The electrical side of this equivalent circuit represents the effect of the resistance R_e, the nonlinear inductance $L_e(x, i)$ and the back EMF generated by the velocity v and the force factor $Bl(x)$. The electro-dynamical driving force $Bl(x)\underline{i}$ and the reluctance force F_m, which is a second nonlinear effect of the nonlinear inductance $L_e(x, i)$, excite the mechanical system, comprising the nonlinear compliance $C_{ms}(x) = 1 / K_{ms}(x)$, moving mass M_{ms}, mechanical resistance R_{ms} and a load Z_{load}.

5 Measurement of Loudspeaker Nonlinearities

The loudspeaker nonlinearities can be measured by using different techniques as defined in the IEC standard 62458.

5.1 Static Measurement

The static measurement as illustrated in Figure 8 uses a DC signal as stimulus (e.g. a constant force) and measures a state variable (e.g. displacement of the coil) of the loudspeaker under steady-state condition. The measurement is repeated for other values of the DC signal, eventually providing the force-deflection curve, which is the basis for calculating the nonlinear stiffness characteristic. Thus the measurement is time-consuming due to the number of points required to sample the nonlinear curve. And there are two more disadvantages. Visco-elasticity of the suspension material cause creep and hysteresis in the displacement, which are not found in loudspeakers operated at higher frequencies. The static measurement technique is less suitable for identifying the inductance nonlinearity, because the DC stimulus generates no temporal derivative of the magnetic flux, and no back induced voltage at the terminals.

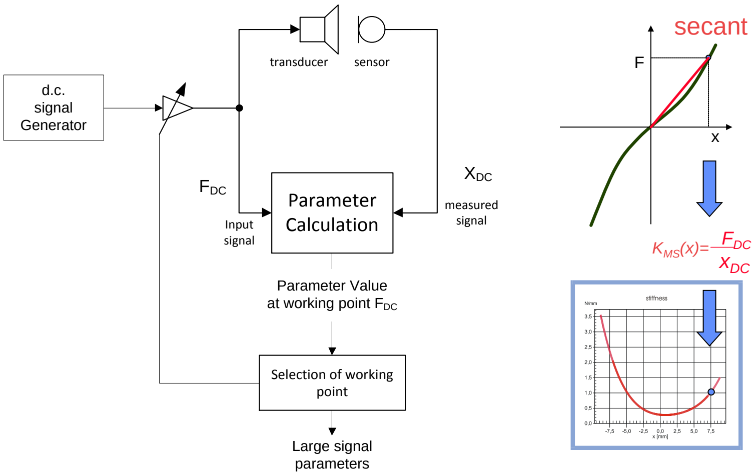


Figure 8: Static measurement of loudspeaker nonlinearity

5.2 Dynamic Method

The full dynamic method uses an AC stimulus with sufficient amplitude and bandwidth, such as music or an audio-like signal (noise). Usually, there is no DC component in the stimulus.

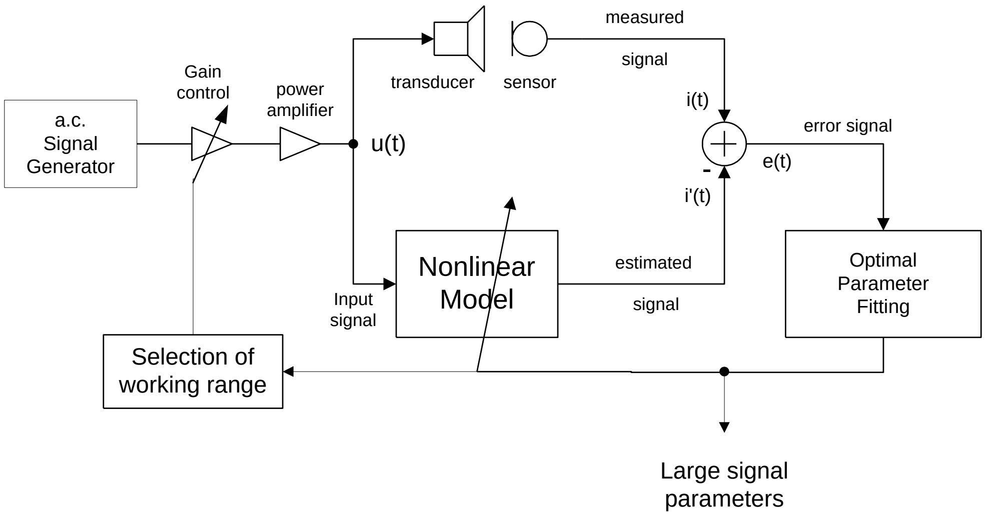


Figure 9: Full dynamic identification of the nonlinear lumped parameter model by measuring voltage *u*(*t*) and current *i*(*t*) at the loudspeaker terminals

5.2.1 Parameter Identification

The measurement of voltage and current at the loudspeaker terminals allows the identification of the loudspeaker's lumped parameter model (see Figure 7) in the electrical domain. The parameter estimates are permanently updated by minimizing an error signal $e(t) = i(t) - i'(t)$ which is the difference between the measured and the estimated current. The ratio E_i of the maximum error and the maximum peak current within an update interval (1s) describes the accuracy of the system identification. The gain of the power amplifier can also be identified by an adaptive technique where the relative error measure E_u describes the discrepancy between estimated and measured terminal voltage.
The electrical resistance R_e and the inductance $L_e(x_{rel})$ nonlinearity can be directly identified in Ohm and Henry. The back EMF defined by $Bl(x)v$ can be used for monitoring the mechanical system and identifying the resonance frequency f_s $(x = 0)$ and the quality factors $Q_{ms}(x = 0)$, $Q_{es}(x = 0)$ and $Q_{ts}(x = 0)$ at the rest position $x = 0$. The electrical measurement also provides the relative force factor nonlinearity $Bl(x_{rel}) / Bl(x = 0)$ and stiffness nonlinearity $K_{ms}(x_{rel}) / K_{ms}(x = 0)$, which reveals the nonlinear curve shape versus the relative displacement x_{rel} with $-1 < x_{rel} < 1$.

5.2.2 State Identification

The system identification (also based on voltage and current monitoring) provides the instantaneous voice coil displacement $x_{rel}(t)$ and other derived mechanical signals (velocity, acceleration) as well, and even the predicted sound pressure output $p(t)$ at any time during the measurement. The mechanical and acoustical signals are relative signals.
An optional laser sensor can be used to measure voice coil displacement and to identify the force factor $Bl(x = 0)$ as a physical quantity calibrated in N/A. The accuracy of this identification can be evaluated by the relative error E_x describing the discrepancy between measured and modeled voice coil displacement. The error E_x indicates inadequate modeling (e.g. a 2nd-order model has been applied to a vented box system) and optical problems in the laser measurement. It is recommend to use the laser information for checking the polarity of the speaker and proper connection of the transducer terminals to the speaker cable which affect the orientation of the displacement (negative displacement should move the coil inwards to the back-plate).
Furthermore, the laser head provides a rough estimate of all mechanical parameters and state variables. A more accurate calibration can be realized by importing a known small signal parameter ($Bl(x = 0)$ or M_{ms}) measured by a small signal measurement (LPM), which is more dedicated for this purpose.
The identification of the electrical DC resistance $R_e(t)$ versus measurement time t is also the basis for calculating the increase of the voice coil temperature ΔT_v during the measurement.

5.2.3 Protection of the Transducer

The measurement of the transducer starts in the small signal domain where the stimulus cannot generate a significant heating of the voice coil and the nonlinearities are negligible. The amplitude of the stimulus is slowly increased in the "Enlargement Mode" while input power, voice coil temperature, nonlinear force factor $Bl(x)$ and nonlinear stiffness $K_{ms}(x)$ are permanently identified. The maximum amplitude of the stimulus is found if either input power, voice coil temperature or the variation of the nonlinear parameter exceeds a user-defined threshold to avoid any thermal and mechanical overload. After finding the limits of the working range for the particular transducer, the "Nonlinear Mode" uses a slow learning speed to ensure the highest accuracy in the adaptive parameter identification.

5.2.4 Distortion Analysis

The identification of the nonlinear parameters in the lumped parameter model is the basis for calculating the peak ratio of the distortion D_B, D_C, D_L and $D_{L(i)}$ generated by $Bl(x)$, $C_{ms}(x)$, $L_e(x)$ and $L_e(i)$ in the predicted sound pressure output signal p_{total}.

5.3 Interpretation of Nonlinear Parameters

The curve shape of the nonlinear parameters provides valuable information on the physical cause and nature of the nonlinearity and is directly related to the properties of the parts used in the loudspeaker assembly.

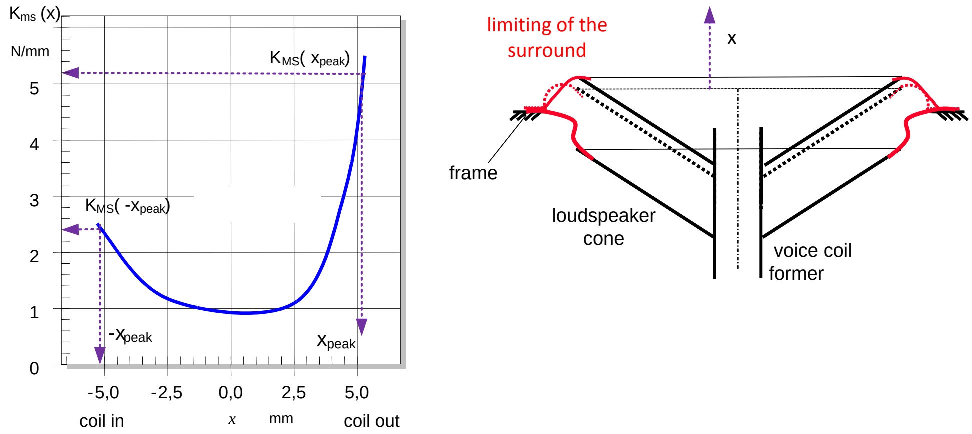


Figure 10: Asymmetry of the $K_{ms}(x)$-characteristic caused by limiting of the suspension

5.3.1 Asymmetry of the Stiffness Characteristic

The asymmetrical shape of the corrugation rolls in the spider or surround and the various combinations of suspension parts may cause an asymmetry in the stiffness curve $K_{ms}(x)$. For example a limiting of the surround at positive excursion as shown on the right-hand side of Figure 10 generates an asymmetrical stiffness characteristic as shown on the left-hand side. Such asymmetry is an undesired property of the suspension because it increases the nonlinear distortion and, when an AC signal is applied a DC component in the displacement moves the coil to the softer side of the suspension.

The asymmetry of the $K_{ms}(x)$-curve can be assessed by a single value:

$$A_K(x_{\text{peak}}) = \frac{2\left(K_{\text{ms}}(-x_{\text{peak}}) - K_{\text{ms}}(x_{\text{peak}})\right)}{K_{\text{ms}}(-x_{\text{peak}}) + K_{\text{ms}}(x_{\text{peak}})} 100\%$$

using the stiffness at negative and positive peak displacement $\pm x_{peak}$ of the measured K_{ms}-curve. The sign of the A_K-value corresponds with the sign of the DC displacement generated dynamically by the nonlinear rectification process.

The stiffness value $K_{ms}(x = 0, x_{peak})$ at the rest position $x = 0$ is not a constant but depends on peak displacement generated by the stimulus before. This behavior can be explained by the visco-elastic behavior of the suspension material (rubber, impregnated fabric, foam, ...) which causes temporary changes in the material properties.

5.3.2 Asymmetry of the Force Factor Characteristic

The asymmetry of the $Bl(x)$ also initiates a rectification of the AC signal, generating a DC displacement moving the coil away from the Bl-maximum and increasing the asymmetry dynamically. This process is the cause of loudspeaker instability and excessive 2nd-order harmonic and intermodulation distortion.

Symmetry Point x_{sym} is a simple measure for assessing the asymmetry of the force factor characteristic. This value is defined by

$$Bl(x_{\text{sym}} - x_{\text{ac}}) = Bl(x_{\text{sym}} + x_{\text{ac}})$$

where x_{sym} is a virtual shift x_{off} of the coil, generating the same Bl-value for positive and negative peak displacement $\pm x_{ac}$ as shown in Figure 11. The symmetry point x_{sym} varies with the peak displacement x_{ac} if the curve is not only shifted by a fixed offset but has a twisted shape.

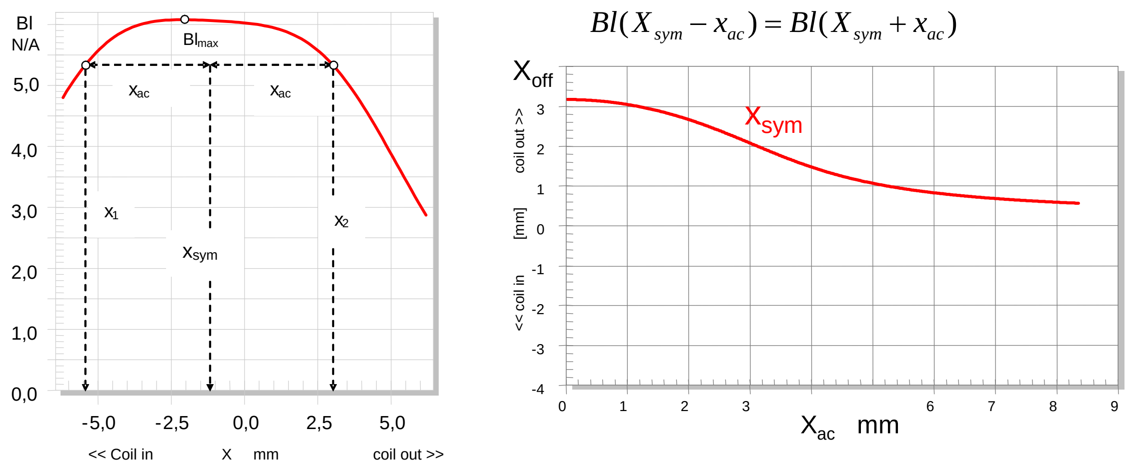


Figure 11: Definition of symmetry point $x_{sym}(x_{ac})$ versus peak displacement x_{ac} generated by the stimulus

For a signal generating low peak displacement, the symmetry point indicates the maximum of the *Bl*(*x*) curve. For high peak displacement x_{ac} the symmetry point x_{sym} describes the virtual shift x_{off} required to generate symmetrical decay of the slopes in the *Bl*(*x*)-curve. The *Bl* symmetry point is a useful criterion to determine the optimal rest position of the coil, considering the *Bl* Asymmetry A_{Bl}, defined by:

$$A_{Bl}(x_{ac}\,,\,x_{off}) = \frac{Bl(x_{off}+x_{ac}) - Bl(x_{off}-x_{ac})}{Bl(x_{off}-x_{ac}) + Bl(x_{off}-x_{ac})}.$$

The measured A_{Bl} describes the relative difference between the *Bl*-value of two points symmetrically located in a central working point x_{off} (shifted rest position of the voice coil) at the distance of the peak displacement x_{ac}.

The asymmetry is negligible if the A_{Bl} is smaller than 5 % and a correction of the rest position is not required. This case depends on the peak displacement x_{ac} and the location of the central working point x_{off} which corresponds to the shifted rest position of the voice coil, and can be represented as a grey area in the Figure 12. For small peak displacement $x_{ac} < x_{Bl\text{-asym}}$ the symmetry region is relatively wide and includes the current voice coil rest position at $x_{off} = 0$ due to the plateau region depicted in the *Bl*(*x*) in the upper left diagram of the Figure 12. The blue dotted line representing the current rest position of the coil at $x_{off} = 0$ leaves the grey area at the critical peak displacement $x_{Bl\text{-asym}}$. At higher amplitudes $x_{ac} > x_{Bl\text{-asym}}$ the current rest position is beyond the symmetry range and the voice coil should be shifted to a new rest position $x_{off} = 1.5$ mm. This ensures that the coil's windings leave the gap symmetrically for positive and negative displacement at high amplitudes. The symmetry region is very narrow at high values of the peak displacement x_{ac} due to the steep slopes of the *Bl*(*x*)-curve.

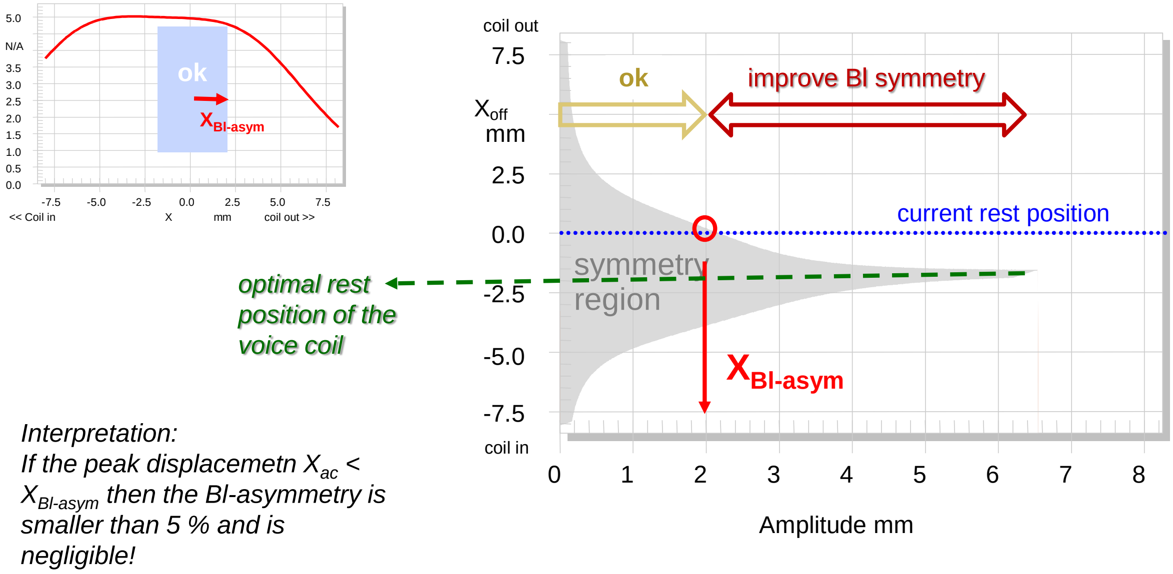


Figure 12: Assessing the symmetry of the *Bl*(*x*)-characteristic and finding the optimal rest position of the voice coil

Electro-dynamical transducers with an equal-length configuration as shown in Figure 3 have a narrower *Bl*-symmetry region and require a careful adjustment of the voice coil rest position. This is because there is no plateau in *Bl*(*x*)-profile but distinct maximum with steep slopes falling to negative and positive displacement.

5.4 Maximal Peak Displacement $X_{max10\%}$

The maximal peak displacement $X_{max10\%}$ of the voice coil is an important parameter for assessing the mechanical capabilities of the transducer limiting the sound reproduction at low frequencies. This value is defined according IEC standard 62458 as the peak displacement of the voice-coil, at which the maximum value of either the total harmonic distortion or modulation distortion is equal to a defined threshold d = 10 %. Alternatively, this value can be derived from the shape of the loudspeaker nonlinearities depending on the voice coil displacement *x*. For each dominant nonlinearity a separate displacement limit is introduced:

- X_C displacement *x* limited by compliance nonlinearity
- X_{Bl} displacement *x* limited by force factor nonlinearity
- X_L displacement *x* limited by inductance nonlinearity

The minimal displacement limit corresponds approximately with the maximal peak displacement $X_{max,10\%}$ generating 10 % distortion.

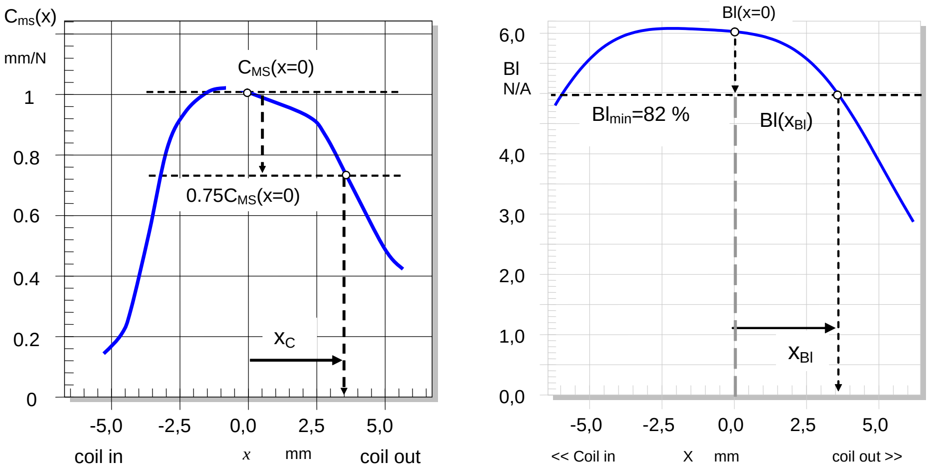


Figure 13: Calculation of the Displacement Limits X_C and X_{Bl} from the nonlinear compliance $C_{ms}(x)$ and force factor *Bl*(*x*)

5.4.1 Displacement Limit X_{Bl} and X_C

The left-hand side in
Figure 13 shows the calculation of the peak displacement X_C limited by nonlinear compliance $C_{ms}(x)$. This limit is the minimal displacement where the compliance decreases to 75 % of the compliance value at the rest position $C_{ms}(X_C) = 0.75\ C_{ms}(x = 0)$. For a single-tone stimulus a transducer would generate about 10 % harmonic distortion in the sound pressure output if the maximum voice coil displacement equals X_C.
The right-hand side shows the calculation of the peak displacement X_{Bl} defined by the minimal displacement, where the force factor decreases to 82 % of the force factor value at the rest position $Bl(X_{Bl}) = 0.82\ Bl(x = 0)$. A transducer with a peak displacement $x_{peak} = X_{Bl}$ generates about 10 % intermodulation distortion in the sound pressure output using a two-tone stimulus.

6 Preparatory Questions

Check your theoretical knowledge before you start the regular training. Answer the questions by selecting all correct responses (sometimes, there will be more than one).

QUESTION 1: Are there any positive aspects of the loudspeaker nonlinearities?

- □ **MC a:** Nonlinearities in the motor and suspension limit the maximal peak displacement and provide a natural mechanical protection of the voice coil former against bottoming.
- □ **MC b:** Force factor nonlinearity is directly related with the efficiency of the transducer in the pass-band ($f > f_s$). For example an equal-length configuration provides a higher *Bl*-value at the rest position and for an ordinary audio signal more acoustical output power than an overhang topology. This reduces the power consumption of portable audio devices and extends the battery lifetime.
- □ **MC c:** A loudspeaker with a nonlinear force factor and stiffness characteristic may be smaller, lighter and less expensive than a transducer with more linearity.
- □ **MC d:** Some loudspeaker nonlinearities (e.g. nonlinear stiffness of a subwoofer) may generate nonlinear distortion which is acceptable and even beneficial in particular applications (e.g. enhancing the bass performance).

QUESTION 2: Why is the direct measurement of the nonlinearities useful in loudspeaker diagnostic and design?

- □ **MC a:** The nonlinear parameters reveal the physical cause of the distortion, while distortion measurements reveal a symptom of the nonlinear system.
- □ **MC b:** The nonlinear parameters do not require physical modeling of the loudspeaker, but the distortion measurement requires a precise model.
- □ **MC c:** The nonlinear parameters are directly related with the geometry and the material of the components.
- □ **MC d:** The nonlinear parameters describe the transducer and are to a large extent independent of the properties of stimulus (contrary to distortion measurement).

QUESTION 3: What are the differences between dynamic and static ways of measuring nonlinear parameters?

- □ **MC a:** The dynamical measurement can be performed while supplying an ordinary audio signal (e.g. music) as stimulus to the transducer. The static measurement usually applies a DC signal (e.g. a constant force) as test signal, which causes a different behavior (e.g. suspension creep) due to the visco-elastic properties of the material.
- □ **MC b:** The static measurement is more time consuming than a dynamic measurement.
- □ **MC c:** There are no differences between dynamic and static methods of measuring nonlinear loudspeaker parameters.

QUESTION 4: Which characteristics (parameter and state information) can be identified by measuring voltage and current at the loudspeaker terminals only?

- □ **MC a:** Increase of the voice coil temperature by monitoring the variation of the DC resistance R_e
- □ **MC b:** Resonance frequency, quality factors Q_{ms}, Q_{es} and Q_{ts}
- □ **MC c:** Electrical parameters which represent moving mass, compliance, and the mechanical and acoustical losses.
- □ **MC d:** Relative mechanical characteristics such as the nonlinear curve shape of force factor characteristic $Bl(x_{rel}) / Bl(x = 0)$ versus relative voice coil displacement $x_{rel} = x / x_{peak}$.
- □ **MC e:** The voice coil displacement in mm (without using additional information provided by a laser sensor or an imported mechanical parameter).

QUESTION 5: Can a dynamic parameter measurement technique developed for electro-dynamical transducer (e.g. LSI woofer) also be used to identify the nonlinear parameter of electro-static transducers?

- □ **MC a:** Yes, all electro-acoustical transducers have significant nonlinearities.
- □ **MC b:** No, the transduction principle is different and different measurement techniques are required to consider the particularities of the physical models.

7 Measurement Tasks with Database (no hardware required)

Step 1: View the demo movie ***Loudspeaker Nonlinearities*** to see how a practical measurement of the linear lumped parameters is performed.

Step 2: Download from the website www.klippel.de/training the software ***dB-Lab*** and install it on your computer.

Advice: It is recommended to do the following exercises offline and to note the answers of the multiple choice questions on a paper!

7.1 Choosing the Loudspeaker Model

Step 3: Open the database ***"Training 3_Loudspeaker Nonlinearities.kdbx"***. The object ***"woofer 4inch in free air small woofer"*** contains LPM and LSI measurements performed on a small woofer operated in free air clamped in a laser measurement stand without any enclosure. Inspect the results of the small signal measurement of the operation ***"1 LPM TS-Parameters"*** and read the resonance frequency f_s to select the **L**arger **S**ignal **I**dentification module (LSI) which provides the proper transducer model.

QUESTION 6: Which model is capable of modeling the transducer under test?

- □ **MC a:** LSI Woofer, (f_s < 400 Hz), free air
- □ **MC b:** LSI Woofer Box, (f_s < 400 Hz), enclosure sealed
- □ **MC c:** LSI Woofer Box, (f_s < 400 Hz), enclosure vented
- □ **MC d:** LSI Tweeter, (f_s > 200 Hz)

7.2 Measurement Procedure

Step 4: The result of the first measurement is stored in the operation ***"2a LSI Clim 50% without laser"***. Open the result window ***"Temperature, Power"*** in this operation and view the progress of the measurement by dragging the pink vertical cursor line (in the beginning it's black) to the left side at the beginning (t = 0) of the measurement. Press the SHIFT key and the right arrow key at the same time to move the cursor to later times and to view the progress of the measurement as an animation.

Step 5: View the result windows ***"State"*** and force factor ***"Bl (X)"*** while moving the time cursor in window ***"Temperature, Power"*** to the time instant when the "Linear Mode 3(7)" is finished and "Enlargement Mode 4(7)" begins.

QUESTION 7: What is the difference between the two modes?

- □ **MC a:** The "Linear Mode 3(7)" provides exact linear parameters (T/S parameters).
- □ **MC b:** The nonlinear curves are flat horizontal lines in the "Linear Mode 3(7)" and it is assumed that the transducer is operated at sufficiently small amplitudes where the nonlinearities are negligible. The protection of the loudspeaker against mechanical overload becomes active at the beginning of the "Enlargement Mode 4(7)" where the nonlinear parameter identification becomes active.
- □ **MC c:** The increase of the voice coil temperature Delta T_v is zero during the "Linear Mode 3(7)" because the instantaneous voice coil resistance R_e is measured and used as a reference value representing the temperature at the beginning of the measurement. The thermal protection of the transducer becomes active in the "Enlargement Mode 4(7)" where the increase of voice coil Delta T_v is available.
- □ **MC d:** The electrical input power is almost constant at the end of the "Linear Mode 3(7)" but increases slowly in the "Enlargement Mode 4(7)" until the limits of the permissible working range (defined according to the protection parameters) are determined.

7.3 Protection Limits

Step 6: Set the cursor at the end of the measurement in the result window ***"Temperature, Power"*** (the cursor becomes black). Open the result window force factor ***"Bl (X)"*** which shows the relative force factor ratio $Bl(x) / Bl(x = 0)$ versus the relative displacement x / x_{prot}. Read the minimal force factor ratio in the working range $Bl_{min} = \text{MIN} \{Bl(x) / Bl(x = 0)\}$ between negative displacement -x_{prot} and positive peak displacement x_{prot}.

Step 7: Open the result window compliance ***"Cms (X)"*** which shows the relative compliance ratio $C_{ms}(x) / C_{ms}(x = 0)$ versus the relative displacement x / x_{prot}. Read the minimal compliance ratio in the working range $C_{min} = \text{MIN} \{C_{ms}(x) / C_{ms}(x = 0)\}$ between negative displacement -x_{prot} and positive peak displacement x_{prot}.

Step 8: Read the real electrical input power P_{real} and the increase of the voice coil temperature ***"Delta Tv"*** in the result window ***"Temperature, Power".***

Step 9: Compare the characteristics Delta T_v, Bl_{min}, C_{min}, P_{real} with the corresponding limit values T_{lim}, Bl_{lim}, C_{lim} and P_{lim} and respectively, presented in parenthesis in result window ***"State"*** and defined on property page ***"Protection"***.

QUESTION 8: Which characteristic limits the working range?

- □ **MC a:** The increase of the voice coil temperature Delta T_v
- □ **MC b:** The minimal force factor ratio Bl_{min}
- □ **MC c:** The minimal compliance ratio C_{min}
- □ **MC d:** The real input power P_{real}

7.4 Laser Sensor

Step 10: Open the operation ***"2b LSI Clim 50%"*** which is measured by using a laser sensor providing the voice coil displacement. Compare the result windows ***"State"***, ***"Bl (X)"***, ***"Kms (X)"*** and ***"Temperature, Power"*** of this operation with the corresponding result windows in operation ***"2a LSI Clim 50% without laser"***.

QUESTION 9: What are the differences between operation ***2a*** and ***2b***?

- □ **MC a:** The operation 2a shows mechanical parameters as relative quantities because no laser is used and no mechanical parameter is imported. Operation 2b derives the force factor from the measured displacement signal and presents the mechanical parameters as absolute quantities in mechanical units (e.g. force factor $Bl(x)$ in N/A).
- □ **MC b:** There is a significant difference in the relative curve shape of the nonlinear parameters $Bl(x)$ and $K_{ms}(x)$.
- □ **MC c:** There is a significant difference in the permissible working range expressed by Delta T_v, Bl_{min}, C_{min}, P_{real} in the result window State.
- □ **MC d:** The operation 2b using the laser sensor displays the labels “coil in” and “coil out” revealing the orientation of the nonlinear curves with respect to the movement of the coil. This information is not available in operation 2a using no laser.

Step 11: Open the result window ***“Cms (X)”*** in the operation ***“4c LSI Error”*** and check whether the label “coil in” appears for negative displacement according to general conventions.

QUESTION 10: Why does the label “coil in” point to positive displacement?

- □ **MC a:** Laser is not calibrated properly (the distance was increased instead of reduced in the calibration process).
- □ **MC b:** Laser is directed to the rear side of the cone.
- □ **MC c:** Loudspeaker is equipped with shorting rings.
- □ **MC d:** Loudspeaker terminals are connected to the DA in reverse polarity.

7.5 Reliability of the Measurement

Step 12: Open the result window ***“Error (t)”*** and view the identification errors $E_i(t)$, $E_x(t)$ and $E_u(t)$ versus measurement time t.

QUESTION 11: What does the error $E_i(t)$ reveal?

- □ **MC a:** $E_i(t)$ describes the disagreement between measured and predicted electrical input current i versus time t.
- □ **MC b:** A high value of the error $E_i(t)$ may be caused by a discrepancy between the model and the transducer under test.
- □ **MC c:** A high value of the error $E_i(t)$ may be caused by a limiting of the voltage and current sensors at high amplitudes (an additional warning will also be generated).
- □ **MC d:** $E_i(t)$ reveals linear and nonlinear distortion generated by the power amplifier.

QUESTION 12: What does the error $E_u(t)$ reveal?

- □ **MC a:** $E_u(t)$ describes the disagreement between input and output signal of the power amplifier.
- □ **MC b:** $E_u(t)$ reveals linear and nonlinear distortion and noise generated by the power amplifier due to clipping, time delay and cut-off frequency of the high pass.
- □ **MC c:** A high value of the error $E_u(t)$ may be caused by a discrepancy between the model and the transducer under test.
- □ **MC d:** There is no laser connected.

QUESTION 13: What does the error $E_x(t)$ reveal?

- □ **MC a:** Laser sensor is not calibrated correctly (measured displacement is too low or too high).
- □ **MC b:** Failure of the optical measurement of the displacement using the laser sensor (wrong distance, optical obstacle hiding the target point for the sensor, target surface is not reflecting).
- □ **MC c:** Linear or nonlinear distortion of the power amplifier(e.g. limiting) will not affect the displacement error E_x because the voltage and current measured at the loudspeaker terminals are used for calculating voice coil displacement x.
- □ **MC d:** There is no laser connected.

QUESTION 14: How can the accuracy of the parameter identifications be checked?

- □ **MC a:** A low value of the error E_i ($E_i < 30$ %) shows that modeled electrical input current corresponds with the measured current i.
- □ **MC b:** A low value of the error E_x ($E_x < 20$ %) shows that modeled mechanical displacement corresponds with the measured displacement x. However, this criterion requires that the laser sensor measures the displacement accurately at sufficient signal-to-noise level.
- □ **MC c:** A high value of the error E_u ($E_u > 50$ %) shows that the measured voltage at the terminals does not correspond with the signal at the amplifier input. However, moderate distortion generated by the amplifier has no influence on the accuracy of the measured parameter because the voltage and current at the loudspeaker terminals are used for system identification.

7.6 Import of Calibration Parameter from LPM

Step 13: Select the operation ***"1 LPM TS-Parameters"*** and open the property page ***"Im/Export"***. Click on ***"Export to Clipboard"***. Select the operation ***"2a LSI Clim 50% without laser"*** and click on ***"Import from Clipboard"*** button on property page ***"Im/Export"***. The relative mechanical parameters and the relative displacement will be replaced by absolute values by using the imported parameters.

QUESTION 15: Why is the import of the force factor value $Bl(x = 0)$ and/or moving mass M_{ms} recommended?

- □ **MC a:** The Linear Parameter Measurement (LPM) measurement determines the lumped parameters in the small signal domain at highest accuracy considering visco-elastic effects (creep) at very low frequencies and irregularities in the impedance (lossy inductance) high frequencies.
- □ **MC b:** The Large Signal Identification (LSI) using a laser sensor provides a value of $Bl(x = 0)$ and M_{ms} which is more accurate than a conventional small signal measurement.
- □ **MC c:** The Large Signal Identification (LSI) operated without a laser sensor is basically an electrical measurement and may be applied to a loudspeaker or any other electro-dynamical transducer operated in a hostile environment (climate chamber). In this case the mechanical characteristics may be calibrated by an import of at least one mechanical parameter ($Bl(x = 0)$ or M_{ms}) known from the specification of the loudspeaker type.

7.7 Consequences of Loudspeaker Nonlinearities

Step 14: Open the result window ***"Cms (X)"*** in the operation ***"2b LSI Clim 50%"*** and inspect the nonlinear compliance. Right-click to activate the cross cursor and search for smallest displacement X_C corresponding with a compliance value $C_{ms}(X_C) = 0.75\ C_{ms}(x = 0)$ and generating about 10% harmonic distortion for a sinusoidal tone signal ($f_1 = f_s$).

QUESTION 16: What is the displacement X_C of the loudspeaker tested in ***"2b LSI Clim 50%"***?

- □ **MC a:** 1.2 mm
- □ **MC b:** 0.5 mm
- □ **MC c:** 2.0 mm
- □ **MC d:** 0.1 mm

Step 15: Open the result window ***"Bl (X)"*** in the operation ***"2b LSI Clim 50%"*** and inspect the nonlinear force factor. Activate the cross cursor by using the right-mouse button and search for smallest displacement X_{Bl} corresponding with a force factor value $Bl(X_{Bl}) = 0.82\ Bl(x = 0)$ and generating about 10 % intermodulation distortion for a sinusoidal two tone signal ($f_1 = f_s$ and $f_2 = 1.5\ f_s$) displacement X_{Bl}.

QUESTION 17: What is the displacement X_{Bl} of the loudspeaker tested in ***"2b LSI Clim 50%"***?

- □ **MC a:** 0.3 mm
- □ **MC b:** 1.7 mm
- □ **MC c:** 2.0 mm
- □ **MC d:** 3.0 mm

Step 16: Open the result window ***"Nonlinear Parameters"*** in the operation ***"2b LSI Clim 50%"*** and compare your reading with the displacement limits X_C, X_{Bl}, X_L where nonlinear compliance $C_{ms}(x)$, force factor $Bl(x)$ and inductance $L(x)$ respectively, generate 10 % harmonic or intermodulation distortion.

QUESTION 18: Determine the nonlinearity having the smallest displacement limit which provides the $X_{max10\%}$-value of the loudspeaker.

- □ **MC a:** Compliance $C_{ms}(x)$ of the suspension
- □ **MC b:** Force factor $Bl(x)$
- □ **MC c:** Doppler effect
- □ **MC d:** Inductance $L(x)$

7.8 Influence of the Stimulus

Open the result window ***"Distortion"*** in the operation ***"2b LSI Clim 50%"*** and view the nonlinear distortion generated in the sound pressure output by each nonlinearity. Compare the maximal peak value D_C, D_B, D_L and $D_{L(i)}$ over time t.

QUESTION 19: Why do the values of the distortion rise over time?

- □ **MC a:** The voltage of the stimulus is increased during the "Enlargement Mode" and the higher amplitude of the state variables (displacement, current, …) activates the loudspeaker nonlinearities.
- □ **MC b:** The adaptive parameter estimation requires some time to converge to the optimal parameter values. The system identification provides the nonlinear parameters at the highest accuracy at the end of the "Nonlinear Mode".

QUESTION 20: Which nonlinearity causes the highest peak value of the nonlinear distortion in the sound pressure output at the end of the measurement?

- □ **MC a:** D_C representing compliance $C_{ms}(x)$ of the suspension
- □ **MC b:** D_B representing force factor $Bl(x)$
- □ **MC c:** D_L representing inductance $L(x)$ versus displacement x
- □ **MC d:** $D_{L(i)}$ representing inductance $L(i)$ versus current i

Step 17: Open the results window ***"Distortion"*** in the measurement ***"3 LSI Clim 50% white noise"*** which uses white noise as stimulus band-pass filtered from 75 Hz to 1.5 kHz as shown in property page ***"Generator"***. Compare the maximal peak value D_C, D_B, D_L and $D_{L(i)}$ with the corresponding values in the operation ***"2b LSI Clim 50%"*** where a pink noise signal is used as a stimulus.

QUESTION 21: Do the spectral properties of the stimulus affect the generation of the distortion?

- □ **MC a:** No, the generation of distortion components is independent of the properties of the stimulus.
- □ **MC b:** Yes, the distortion generated by the inductance nonlinearity $L(x)$ highly depends on the spectral properties of the stimulus. The white noise stimulus used in ***"3 LSI Clim 50% white noise"*** increases the intermodulation generated by $L(x)$ significantly and makes the $L(x)$ to the dominant source of distortion.

7.9 Loudspeaker Asymmetries

Step 18: Open the result window ***"Bl (X)"*** in the operation ***"2b LSI Clim 50%"*** and compare the $Bl(x)$ with the flipped-over curve $Bl(-x)$.

QUESTION 22: Does a shift of the rest position of the coil towards the back plate (coil in) reduce the asymmetry in the $Bl(x)$-curve?

- □ **MC a:** No, a correction of the voice coil rest position does not affect the curve shape of $Bl(x)$.
- □ **MC b:** No, the coil has to be shifted in the other direction (outwards).
- □ **MC c:** Yes, the asymmetry can be reduced by shifting the rest position of coil inwards.

Step 19: Open the result window ***"Bl Symmetry Range"*** in the operation ***"2b LSI Clim 50%"*** which describes the asymmetry of the *Bl*-curve as a function of amplitude x_{ac} of the stimulus (*x*-axis) and a an offset x_{off} of the rest position (*y*-axis). The symmetry region (grey area) shows the range where the variation of *Bl*-value is small (less than 5 %) and the asymmetry is negligible.

QUESTION 23: Does the symmetry region depend on the amplitude x_{ac} of the stimulus?

- □ **MC a:** Yes, the symmetry region depends on the amplitude x_{ac}. It is larger at small amplitudes (e.g. x_{ac} = 0.1 mm) because an offset in the rest position (*y*-axis) generates only minor asymmetrical variation of the *Bl*-value (there are a constant number of windings in the gap).
- □ **MC b:** No, the symmetry region is independent of the amplitude x_{ac}.
- □ **MC c:** Yes, the symmetry region depends on the amplitude x_{ac}. It is smaller at high amplitudes (e.g. x_{ac} = 1.5 mm) because a small offset will cause a significant variation of the *Bl*-value at positive and negative maxima of the displacement where the slopes of the *Bl*-curve are steep (coil is leaving the gap).

Step 20: Open the result window ***"Bl Symmetry Range"*** in the operation ***"2b LSI Clim 50%"***. Determine the peak displacement $x_{Bl\text{-asym}}$ which is the maximal amplitude where voice coil generates a 5 % *Bl*-variation (maximal amplitude where the rest position lies within the symmetry range).

QUESTION 24: What is the maximal amplitude of the voice coil displacement $x_{Bl\text{-asym}}$ where the asymmetry of the *Bl*-curve is negligible?

- □ **MC a:** 0.3 mm
- □ **MC b:** 0.8 mm
- □ **MC c:** 1.5 mm

Step 21: The symmetry point shown as a red line in the result window ***"Bl Symmetry Range"*** corresponds with the optimal shift of the rest position for a particular amplitude of the sinusoidal stimulus. Using this point as the rest position of the coil generates the same *Bl*-value for positive and negative displacement according to the AC amplitude of the signal. Compare the symmetry point for a very small AC signal (0.2 mm amplitude) with the position of the symmetry point for a large AC signal (1.8 mm amplitude) in the result window ***"Bl Symmetry Range"*** in the operation ***"2b LSI Clim 50%"***.

QUESTION 25: Which symmetry point should be used for correcting the rest position of the voice coil?

- □ **MC a:** The rest position of the coil should be shifted exactly by -0.42 mm because only this value provides perfect symmetry of the *Bl*-curve in the small signal domain (low amplitude $x \approx 0$).
- □ **MC b:** A value between -0.36 mm and -0.2 mm depending on the maximal amplitude x_{ac} specified in the target application. If the amplitude of the displacement x_{ac} is smaller than $x_{Bl\text{-asym}}$ the offset of the rest position is negligible.

QUESTION 26: Does a significant asymmetry of the *Bl*(*x*)-curve reduce the maximal peak value of the displacement limit X_{Bl}?

- □ **MC a:** Yes, an asymmetry causes an earlier decay of the *Bl*-value at one side, a later decay at the other side and provides a smaller value of the maximal peak displacement. This is because this value is defined as the minimal displacement providing 82 % of the *Bl*-value found at the rest position. This reduces the working range even where the *Bl*-value is larger on the other side at the same displacement.
- □ **MC b:** No, an asymmetry of the *Bl*-curve has no influence on the maximal peak displacement generating 10 % harmonic distortion approximately.

Step 22: Open the result window "Kms (X)" in the operation "2b LSI Clim 50%" and compare the stiffness curve Kms(x) with the flipped-over curve Kms(-x). Use the cross cursor to read the Kms-values at the points xpeak = 2 mm and x-peak = -2 mm. Calculate the stiffness asymmetry by dividing the difference by the mean value of the stiffness values according to

$$A_K(x_{\text{peak}}) = \frac{2\left(K_{\text{ms}}(-x_{\text{peak}}) - K_{\text{ms}}(x_{\text{peak}})\right)}{K_{\text{ms}}(-x_{\text{peak}}) + K_{\text{ms}}(x_{\text{peak}})} 100\%.$$

QUESTION 27: How much is the stiffness asymmetry A_K approximately?

- □ **MC a:** 20 %
- □ **MC b:** 47 %
- □ **MC c:** -47 %
- □ **MC d:** -400 %

QUESTION 28: Does the sign of the stiffness asymmetry A_K provide valuable information?

- □ **MC a:** No, the sign of the stiffness asymmetry A_K is always positive.
- □ **MC b:** Yes, it corresponds with the sign of the DC displacement generated by the stiffness asymmetry (positive sign of A_K generates a positive DC displacement away from the back plate).
- □ **MC c:** Yes, it shows the softer side of the suspension. A positive sign of A_K shows that the suspension is softer for positive displacement than for negative.

Step 23: Open the result window ***"Displacement"*** in the operation ***"2f LSI Clim 20%"***. Compare the measured peak and bottom value of the predicted positive and negative peak displacement x_{peak} and x_{bottom}, respectively, with the corresponding values x_{max} (laser) and x_{min} (laser), measured by using the laser sensor.

QUESTION 29: What does the result window ***"Displacement"*** reveal?

- □ **MC a:** The predicted peak and bottom displacement values agree approximately with the values measured by the laser sensor showing that the loudspeaker model fits the transducer under test.
- □ **MC b:** At higher amplitudes the peak displacement in positive direction (x_{peak}) is larger than the peak displacement in negative direction (x_{bottom}). This indicates that a positive DC displacement is dynamically generated by asymmetries in the loudspeaker nonlinearities.
- □ **MC c:** At higher amplitudes the peak displacement in positive direction (x_{peak}) is smaller than the peak displacement in negative direction (x_{bottom}).This indicates that a negative DC displacement is dynamically generated by asymmetries in the loudspeaker nonlinearities.

Step 24: Open the result window ***"PDF (X)"*** in the operation ***"2f LSI Clim 20%"*** which shows the Probability Density Function $PDF(x)$ of the displacement x during the "Nonlinear mode". This curve shows the distribution of the displacement depending on the properties of the excitation signal (noise) and on the behavior of the transducer as well. The coil is most frequently close to the rest position while high excursions are rather rare. That explains why the identification of a linear system and the nonlinearities at small displacement can be accomplished within a few seconds but the measurement of the nonlinearities at the very end of the operating range takes a few minutes. Check the asymmetry of the probability function of the displacement by comparing the original curve with the flipped-over curve $PDF(-x)$. Check the symmetry of the voltage signal applied to the terminals of the transducer in the result window ***"PDF Voltage"***.

QUESTION 30: What causes the asymmetry in the $PDF(x)$ of the displacement?

- □ **MC a:** Loudspeaker nonlinearities (especially asymmetries in the stiffness K_{ms} characteristic) generate an asymmetrical shape of the $PDF(x)$ which corresponds with the DC displacement and differences peak and bottom value of the displacement.
- □ **MC b:** The stimulus used by the measurement system has an asymmetrical $PDF(u)$ of the voltage which also affects the voice coil displacement.

7.10 Parameter Variation over Time

Step 25: Open the result window ***"fs (X)"*** in in the operation ***"2f LSI Clim 20%"*** which shows the instantaneous resonance frequency $f_s(x) = \frac{1}{2\pi}\sqrt{\frac{K_{ms}(x)}{M_{ms}}}$ considering the displacement varying stiffness of the suspension.

Step 26: Open the result window ***"Kms (t), fs (t)"*** in the operation ***"2f LSI Clim 20%"*** to view the variation of the stiffness $K_{ms}(x = 0, t)$ and the resonance frequency $f_s(x = 0, t)$ at the rest position $x = 0$ over time.

Step 27: Compare the stiffness $K_{ms}(x = 0)$ and resonance frequency $f_s(x = 0)$ at the end of the large signal measurement in operation ***"2f LSI Clim 20%"*** with the stiffness K_{ms} and resonance frequency f_s measured at low amplitudes in operation ***"1 LPM TS-Parameters"***.

QUESTION 31: Is the stiffness $K_{ms}(x = 0)$ at the rest position constant?

- □ **MC a:** No, the stiffness of the suspension $K_{ms}(x = 0)$ at the rest position $x = 0$ decreases significantly during the "Enlargement Mode" (150 s < *t* < 300 s) when the amplitude of the voice coil displacement has been increased. There is only a small decrease of the stiffness $K_{ms}(x = 0)$ during the "Nonlinear Mode" (300 s < *t* < 550 s) when the amplitude is almost constant. Visco-elastic mechanisms in the suspension material cause a dependency of the stiffness $K_{ms}(x = 0)$ at the rest position on peak displacement.
- □ **MC b:** Yes, the stiffness at the rest position is always constant.

Step 28: Open the result window ***"Re (t)", "Qes (t)"*** of the operation ***"2f LSI Clim 20%"*** and compare the resistance $R_e(t)$ with the voice coil temperature $T_v(t)$ in the result window ***"Temperature, Power"***.

QUESTION 32: Why do the resistance $R_e(t)$ and increase of the voice coil temperature $T_v(t)$ have a similar curve shape?

- □ **MC a:** The increase of the voice coil temperature T_v is calculated from the increase of the DC resistance R_e.
- □ **MC b:** The increase of the voice coil temperature is independent of the resistance R_e. Any similarity between the two curves is accidental.

Step 29: Select the operation ***"2e LSI Clim 30%"*** which shows the result of a more "aggressive" measurement with weaker protection parameters. Open the result window ***"Bl (X)".*** Copy the curve "*Xp- < X < Xp+"* into the clipboard and paste this curve and the curves from operations ***2b - 2d*** into the result window ***"Bl (X)"*** of the operation ***"2f LSI Clim 20%"***. Compare the shape of the *Bl*-curves.

Step 30: Repeat with the result window ***"K_{ms} (X)"***. Compare the variation of the K_{ms}-curves with the variation of the *Bl*-curves.

QUESTION 33: Does the nonlinear shape of the $K_{ms}(x)$-curve depend on the peak value x_{peak} of the displacement?

- □ **MC a:** No, the curves are almost constant and do not change with the peak displacement x_{peak}.
- □ **MC b:** Yes, there is also a temporary change of the stiffness curves due to visco-elastic behavior of the suspension. Especially the stiffness $K_{ms}(x = 0)$ at the rest position decreases when the amplitude of the stimulus rises.
- □ **MC c:** Yes, there is also permanent change of the stiffness due the break-in effect (exposing a new transducer to the stimulus for the first time) and load-induced fatigue (aging of the suspension).

8 Performing Measurements (Hardware required)

The following instructions provide some tips for practical measurement on loudspeakers of your choice. We recommend starting with a relatively small (4-6 inch) woofer.

8.1 Setup the Hardware

The yellow pages of the 2nd Tutorial in the manual of the LSI provide detailed information on the hardware setup. Here is a short summary of the most important points:

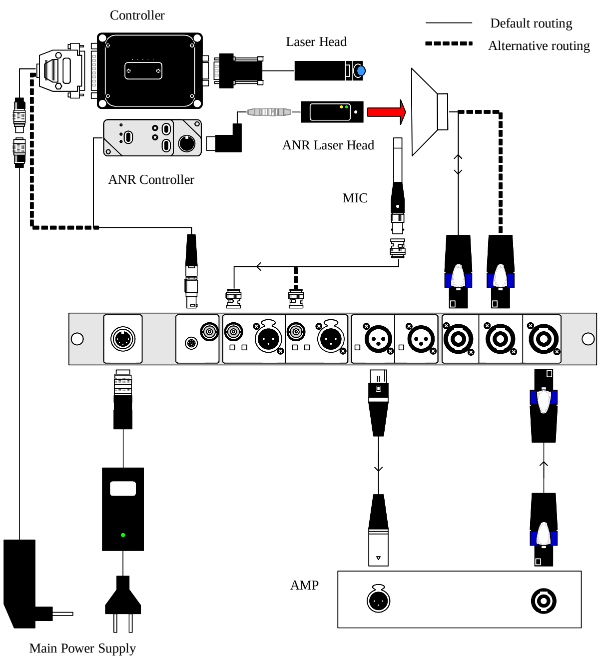


Figure 13 Pin Assignments DA2

Step 31: Connect **XLR Output *OUT1*** on the rear side of the *Distortion Analyzer (DA)* with the **XLR Input** of the Amplifier. Connect the Output of the Amplifier with the DA **SPEAKON Input *AMPLIFIER***. Connect the DA **SPEAKON Output *Speaker 1*** (high current channel) with the loudspeaker terminals. Use the special speaker measurement cable.

Step 32: Connect the laser head (if available) with the controller and link the LEMO plug of the controller into the ***LASER*** marked Input on the rear side of the *DA*.

Step 33: Connect the ***USB* Input** on the Front of the *DA* with the PC.

Step 34: Clamp the loudspeaker solid and orthogonal to the laser beam into the speaker stand. Apply a white dot on the middle of the cone (TippEx® or a small white sticker). Aim the laser beam to the white dot. Bring the laser head to its working range: The yellow LED lights up permanently (ANR-Laser) or the green LED lights up (LD-Laser) (ca. 6 cm)

1.1 Measurement Tasks

Step 35: Open the measurement software *dB-Lab* of the R&D system. Create a new database: click on ***"Project"* → *"Select Database"*** then ***"New"***. Choose a save path and a name. Customize the name of the measurement object 'my driver's name.

Step 36: Select **"New Operation"**. Now *dB-Lab* offers different measurement templates which make the first measurement easier. Select LSI Woofer Driver to measure a woofer with $f_s < 600$ Hz or LSI Tweeter Driver to measure a tweeter having $f_s > 100$ Hz.

Step 37: Right-click on the operation and select ***"Properties"***. Enter the ***diameter*** of the driver in the property page ***"Driver"***.

Step 38: Check the limits in the property page ***"Protection"***. The default limits normally protect the speaker against destruction. If you have a laser, the lumped parameters will be identified in the "Linear Mode" automatically (you can adjust the voltage level with $\boldsymbol{G_{small}}$ on the ***"Protection"*** page.), but we recommend importing the data from a previous LPM to arrive at a more exact measurement.

Step 39: If you have no laser connected, you may import the $Bl(x = 0)$ or M_{ms} measured by a Linear Parameter Measurement (Training 1).

Step 40: Start the measurement by clicking the green arrow.

Step 41: If you have entered the "Enlargement Mode", open the result window ***"State"*** and check the relative error $E_i(t)$ of the modeled current signal. This value should be below 25 % if the model fits the loudspeaker under test.

Step 42: If you are using a laser displacement sensor, check the error $E_x(t)$ in the displacement signal $x(t)$. If this value is larger than 20 %, open the result window $L(x)$ and check that the information "COIL IN" is displayed at negative displacement axis. If this value appears for positive displacement, press the pause button and change the polarity of the speaker cables at the terminals of the loudspeaker. Click pause button again to resume the measurement. Observe the change in the nonlinear inductance curve. The label "coil in" should appear for negative displacement.

Step 43: Does the maximum of the $L(x)$ curve appear at negative displacement? Do you think that the loudspeaker under test uses a shorting ring to reduce and linearize the inductance $L(x)$?

Step 44: If the measurement is finished, the open the result window Temperature, Power. Does the increase of the voice coil temperature limit the maximal amplitude of the stimulus during the measurement?

Step 45: Open the result window ***"Nonlinear Parameters"***. Find the maximal peak displacement $X_{\mathrm{max}10\%}$ by searching for the minimum of the displacement limits X_{Bl}, X_L, X_C. Which nonlinearity limits the peak displacement of the loudspeaker?

Step 46: Open the result window ***"Distortion"*** and search for the nonlinearity generating the highest value of the distortion in the sound pressure output. Does the nonlinearity also limit the maximal peak displacement?

Step 47: View the symmetry of the $Bl(x)$ in the result windows $Bl(x)$. Can the symmetry of the $Bl(x)$ curve be improved by shifting the rest position of the coil? Should the rest position of the voice coil be shifted away or to the back plate of the loudspeaker to improve the symmetry of the $Bl(x)$ curve?

Step 48: Search for the displacement value $x_{\mathrm{max}Bl}$ where the $Bl(x)$ value becomes maximal.

Step 49: Open the result window ***"Bl-symmetry Range"***. Read the symmetry point (red curve) at maximal value of the amplitude (x-axis). Does this value agree with the value x_{sym} shown in the result window ***"Nonlinear Parameter"***. Is the value x_{sym} identical with the value $x_{\mathrm{max}Bl}$? Is the value $x_{\mathrm{max}Bl}$ or x_{sym} a good estimate for a voice coil shift to improve the symmetry of the $Bl(x)$ curve?

Step 50: View the symmetry of the $K_{\mathrm{ms}}(x)$ curves in the result window $K_{\mathrm{ms}}(x)$. Where is the softer side of the suspension?

Step 51: Open the result window ***"PDF (X)"*** and view the probability density function of the displacement. Is the curve symmetrical? Which nonlinearity may cause the asymmetrical shape of the curve?

9 Further Literature

User Manual for the KLIPPEL R&D SYSTEM – *Large Parameter Identification*

Specification S1 *Large Signal Identification* (LSI)

http://www.klippel.de/fileadmin/klippel/Bilder/Our_Products/R-D_System/PDF/S1_LSI.pdf

Know-how Poster *"Loudspeaker Nonlinearities: Causes, Parameters, Symptoms"*

Paper *Loudspeaker Nonlinearities: Causes, Parameters, Symptoms:*
http://www.klippel.de/uploads/media/Loudspeaker_Nonlinearities%E2%80%93Causes_Parameters_Symptoms_01.pdf

Paper *Assessing Large Signal Performance of Transducers*
http://www.klippel.de/fileadmin/klippel/Files/Know_How/Literature/Papers/Assessing_the_large_Signal_performance_of_Loudspeakers_02.pdf

Paper *Measurement of Large Signal Parameters of Electrodynamic Transducer:*
http://www.klippel.de/uploads/media/Measurement_of_Large-Signal_Parameters_99.pdf

Paper *Large Signal Performance of Tweeters, Microspeakers and Horn Drivers:*
http://www.klippel.de/uploads/media/Large_signal_performance_of_tweeters_01.pdf