Hands-On Training 5

Predicting the Nonlinear Loudspeaker Behavior

1 Objectives of the Hands-on Training

- Modeling of the loudspeaker behavior in the large signal domain
- Solving the differential equation in the time domain for arbitrary sinusoidal stimuli
- Evaluation of design choices by virtual variation of the loudspeaker nonlinearities
- Relationship between nonlinear symptoms and loudspeaker parameters
- Interpretation of loudspeaker measurements (Loudspeaker diagnostics)

2 Requirements

2.1 Previous Knowledge of the Participants

It is recommended to do the previous *Klippel Trainings* before starting this training.

2.2 Minimal Requirements

Participants will need the results of the measurement provided in a Klippel database *Training 5 Predicting the Nonlinear Loudspeaker Behavior.kdbx*. A complete setup of the KLIPPEL measurement hardware is not necessary. 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 Module (DIS)
- Simulation Module (SIM)
- Distortion Analyzer DA2
- Laser Sensor + Controller
- Amplifier
- Driver Stand

3 The Training Process

1. Read the theory that follows to refresh your 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 www.klippel.de/training.
6. Receive an email containing a **Certificate with high distinction, distinction or credit** (depending on your performance).
7. Perform some optional measurements on transducers if the hardware is available.

4 Introduction

At low frequencies where the wavelength is large compared to the dimensions of the transducer, the electro-mechanical system can be modeled by the lumped parameter model shown in Figure 1.

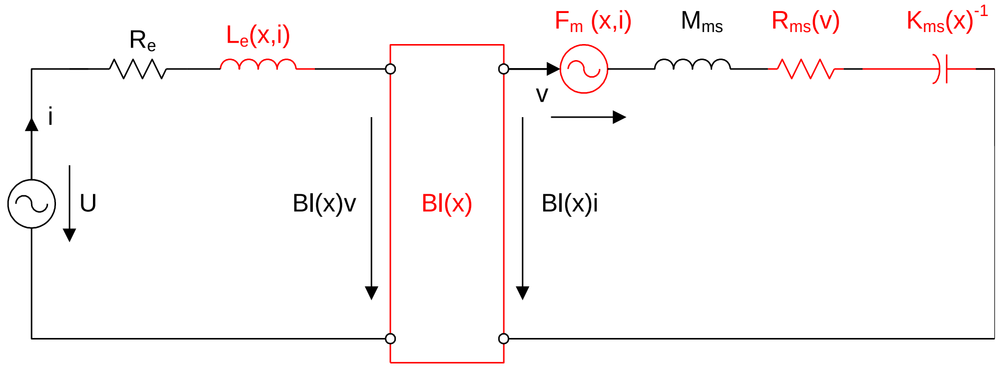

Figure 1: Electro-mechanical transducer represented as an electrical equivalent circuit using linear and nonlinear parameters represented as black and red elements

This equivalent circuit comprises linear and nonlinear parameters as shown in Table 1 below:

R_e	electrical resistance of the voice coil
$L_e(x, i)$	electrical inductance of the voice coil depending on voice coil displacement x and input current i
$Bl(x)$	force factor of the electro-dynamical motor depending on voice coil displacement x
$F_m(x, i)$	reluctance force caused by displacement varying inductance $L_e(x)$ depending on displacement and current
$K_{ms}(x) = C_{ms}(x)^{-1}$	Stiffness (inverse of the compliance) of the mechanical suspension depending on displacement x
M_{ms}	Moving mass of all mechanical parts including air load
$R_{ms}(v)$	Mechanical and acoustical losses varying with voice coil velocity v

Table 1: Lumped parameters description

The linear parameters are constant (e.g. mass M_{ms}), independent of the state of the system, and well known from the linear modeling (see Training 1). The nonlinear parameters (e.g. $Bl(x)$) are nonlinear functions that depend on the instantaneous state of the system such as the displacement x, current i and velocity v. Figure 2 shows the nonlinear integro-differential equation of the electro-mechanical transducer based on the lumped parameter model in Figure 1.

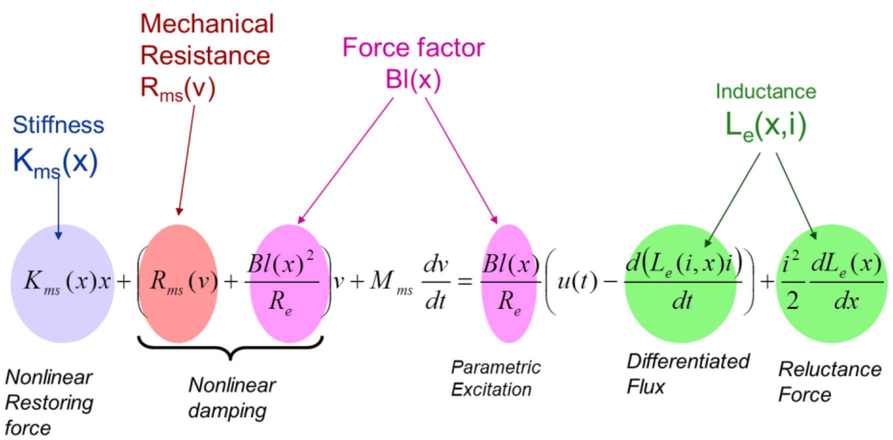

Figure 2: Nonlinear effects in the integro-differential equation of the electro-mechanical transducer under voltage supply

The left side shows the sum of restoring force, inertia and the damping force corresponding with the mechanical stiffness K_{ms}, mechanical resistances $R_{ms}(v)$ and moving mass M_{ms} connected in series, as shown in Figure 1. If the transducer is operated via an amplifier having a low output impedance, the total damping depends on the electrical damping related to the nonlinear dependency $Bl(x)^2/R_e$ versus voice coil displacement x. The nonlinear force factor $Bl(x)$ also causes a variation of the electro-dynamical excitation on the right-hand side of the equation.
The inductance $L_e(x, i)$ has also two nonlinear effects. It causes a variation of the electrical input current at high frequencies, where the self-inductance contributes significantly to the electrical input impedance. The second nonlinear effect is the reluctance force, generating an additional excitation of the mechanical system if the local derivative of the inductance does not vanish (and inductance $L_e(x) \neq$ constant).
The nonlinear integro-differential equation reveals products comprising a nonlinear parameter and a state variable. Both the nonlinear parameter and the state variable are varying with time. This multiplication of time-varying signals causes harmonic and intermodulation distortion and other nonlinear symptoms.

5 Generation of nonlinear distortion

The restoring force $F_{res} = K_{ms}(x)x$ may be described as the product of displacement x and nonlinear stiffness $K_{ms}(x)$. For example, voice coil displacement containing two sinusoidal tones at frequency ω_1 and ω_2 can be described by the equation: $x(t) = X_1 \cos(\omega_1 t) + X_2 \cos(\omega_2 t)$.

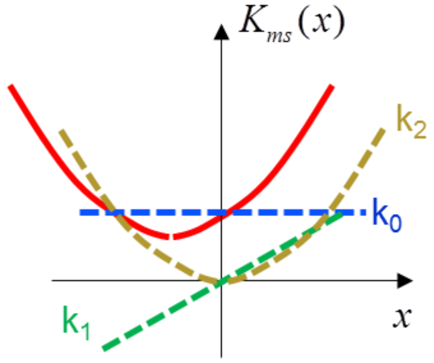

Figure 3: Power series expansion of the stiffness asymmetry

using a truncated power series of the stiffness $K_{ms}(x)$: $K_{ms}(x) = \sum_{n=0}^{\infty} k_n x^n = k_0 + k_1 x + k_2 x^2 + \dots$

Thus, the restoring force is:

$$
\begin{aligned}
F_{res}(t) = K_{ms}(x)x &= k_0 x + k_1 x^2 + k_2 x^3 + \dots \\
&= \frac{k_1}{2}(X_1{}^2 + X_2{}^2) \qquad dc-component \\
&+ (k_0 X_1 + \frac{3}{4} k_2 X_1^3)\cos(\omega_1 t) + (k_0 X_2 + \frac{3}{4} k_2 X_2^3)\cos(\omega_2 t) \qquad fundamentals \\
&+ \frac{k_1}{2}\left[X_1{}^2 \cos(2\omega_1 t) + X_2{}^2 \cos(2\omega_2 t)\right] \qquad 2nd-order\ harmonics \\
&+ \frac{k_2}{4}\left[X_1{}^3 \cos(3\omega_1 t) + X_2{}^3 \cos(3\omega_2 t)\right] \qquad 3rd-orderharmonics \\
&+ k_1\left[X_2 X_1 \cos((\omega_2 - \omega_1)t) + X_2 X_1 \cos((\omega_2 + \omega_1)t)\right] \\
&+ k_2\left[X_2 X_1{}^2 \cos((2\omega_1 - \omega_2)t) + \dots + X_2 X_1{}^2 \cos((2\omega_1 + \omega_2)t)\right] \\
&+ \dots
\end{aligned}
$$

Equation 1

The coefficient k_0 describes the value of the stiffness $K_{ms}(x)$ at the rest position $x = 0$, as illustrated in Figure 3. The constant part appears only in the fundamental components of the restoring force at frequencies ω_1 and ω_2 and corresponds with the T/S parameter used in traditional linear modeling.
The coefficient k_1 in the linear term of the power series of the stiffness $K_{ms}(x)$ generates a dc component in the displacement, 2nd-order harmonic distortion at twice the excitation frequencies $2\omega_1$ and $2\omega_2$, and 2nd-order intermodulation products at the summed and difference frequencies.
The coefficient k_2 weighting the quadratic term generates 3rd-order harmonics at $3\omega_1$ and $3\omega_2$ and a multitude of intermodulation components at all combination frequencies. The coefficient k_2 also generates a nonlinear contribution to the fundamental components at the original excitation frequencies.
The amplitudes of the 2nd and 3rd-order distortion components follow a quadratic and cubic law of the amplitudes X_1 and X_2, respectively. Therefore, the distortion components are negligible if the amplitudes X_1 and X_2 of the displacement are sufficiently small. If the amplitudes X_1 and X_2 are frequency independent, then the amplitudes of the distortion components in the restoring force are independent of the frequencies ω_1 and ω_2. Equation 1 describes a static nonlinear system having no memory and generating an instantaneous output $F_{res}(t)$ for any input signal $x(t)$.
However, voice coil displacement in loudspeakers and other electro-dynamical transducers has a low-pass characteristics and the amplitudes $X_1(\omega_1)$ and $X_2(\omega_2)$ are only constant below resonance frequency f_s. It decreases by 12 dB per octave at higher frequencies. Thus, the nonlinear components in the restoring force $F_{res}(t)$ may be considered as additional distortion exciting the mechanical system and generating a feedback loop, as shown in Figure 4.

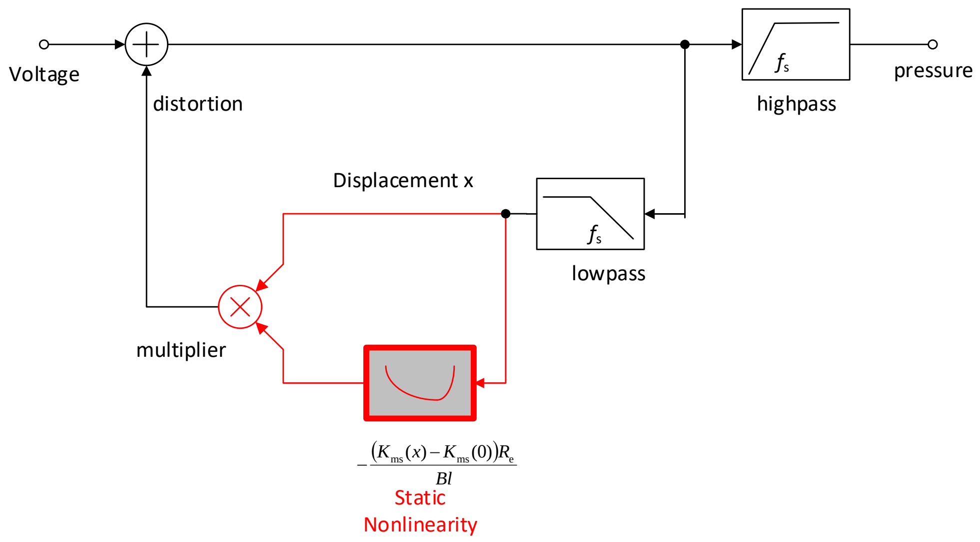

Figure 4: Signal flow chart describing the effect of the nonlinear stiffness $K_{ms}(x)$

The signal flow chart above separates two linear subsystems from the static nonlinearity generating only the nonlinear distortion. The low-pass generating the voice coil displacement prior to the static nonlinearity can be considered to be a pre-filter while the high-pass in Figure 4 behaves as a post-filter shaping the distortion components generated in the static nonlinearity.
In the small signal domain, where the voice coil displacement is small, the output of the multiplier is also small compared to the input voltage and the distortion generated by the nonlinear feedback path can be neglected. Thus, the transducer behaves like a linear high pass between voltage input and sound pressure output.
In the large signal domain the distortion at the output of the multiplier is the same order of magnitude as the input voltage and causes a nonlinear compression effect at low frequencies.
Figure 5 is a more general representation of Figure 4 and can also be applied to other nonlinearities found in the nonlinear differential equation.

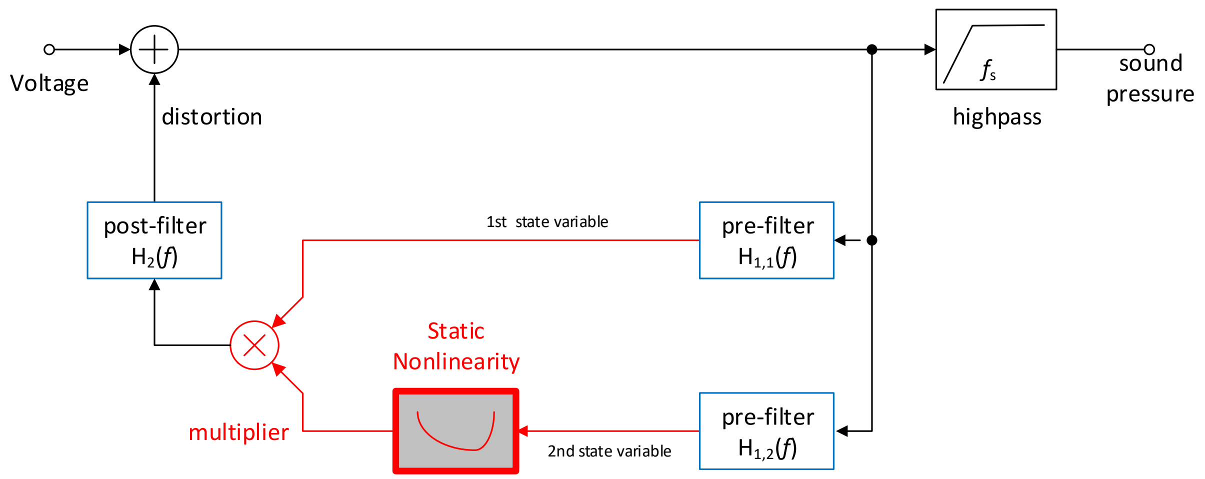

Figure 5: Generalized signal flow chart modeling the generation of nonlinear distortion by a single loudspeaker nonlinearity

Not only the force factor nonlinearity $Bl(x)$, but also the inductance $L_e(x, i)$ requires the multiplication of two different state variables (displacement x and current i). The generation of the nonlinear distortion in the self-induced voltage by $L_e(x, i)$ requires a differentiation of the magnetic flux which corresponds to the additional post filter $H_2(f)$ after the output of the multiplier. While the displacement x is generated by a low pass with a cut-off at the loudspeaker's resonance frequency f_s, the generation of the current requires a stop-band filter attenuating the signal at f_s.

The static nonlinearities are part of a feedback loop in Figure 5. This is important for the generation of higher-order distortion components. Even if the static nonlinearity is represented by a power series expansion truncated after the linear term (represented by coefficient k_1 only), the static nonlinearity produces higher-order components in each loop.

6 Properties of the subfilters for the most important nonlinearities

Table 2 summarizes the most important loudspeaker nonlinearities. The properties of the linear pre- and post-filters are described by typical filter characteristics (band-pass, high-pass, low-pass…) to generate the first and second state variables which are multiplied with each other in the static nonlinearity.

NONLINEARITY	INTERPRETATION	PRE-FILTER $H_{1,1}(f)$ (output)	PRE-FILTER $H_{1,2}(f)$ (output)	POST-FILTER $H_2(f)$
Stiffness $K_{ms}(x)$ of the suspension	Restoring force	Low-pass (displacement x)	Low-pass (displacement x)	1
Force factor $Bl(x)$	Electro-dynamical force	Band-stop (current i)	Low-pass (displacement x)	1
	Nonlinear damping	Band-pass (velocity v)	Low-pass (displacement x)	1
Inductance $L_e(x)$	Self-induced voltage	Band-stop (current i)	Low-pass (displacement x)	Differentiator
	Reluctance force	Band-stop (current i)	Low-pass (displacement x)	1
Inductance $L_e(i)$	Varying permeability	Band-stop (current i)	Band-stop (current i)	Differentiator
Mechanical resistance $R_{ms}(v)$	Nonlinear damping	Band-pass (velocity v)	Band-pass (velocity v)	1
Young's modulus $E(\varepsilon)$ of the material	Cone vibration	Band-pass (strain ε)	Band-pass (strain ε)	1
Speed of sound c(p)	Nonlinear sound propagation (wave steepening)	High-pass (sound pressure p)	High-pass (sound pressure p)	Differentiator
Time delay $\tau(x)$	Nonlinear sound radiation (Doppler effect)	High-pass (sound pressure p)	Low-pass (displacement x)	Differentiator

Table 2: Properties of the pre-filters $H_{1,1}(f)$ and $H_{1,2}(f)$ and the post-filter $H_2(f)$ for the most important loudspeaker nonlinearities

The particular properties of pre- and post-filters in connection with the high-pass in the linear path cause the dynamic nonlinear behavior of the transducer and particular frequency response of the distortion components.

7 Prediction of the Large Signal Behavior

The results of the theoretical modeling (differential equation in Figure 1) and modern identification techniques for measuring transducer parameters are the basis for simulating the vibration and radiation in the small and large signal domain.

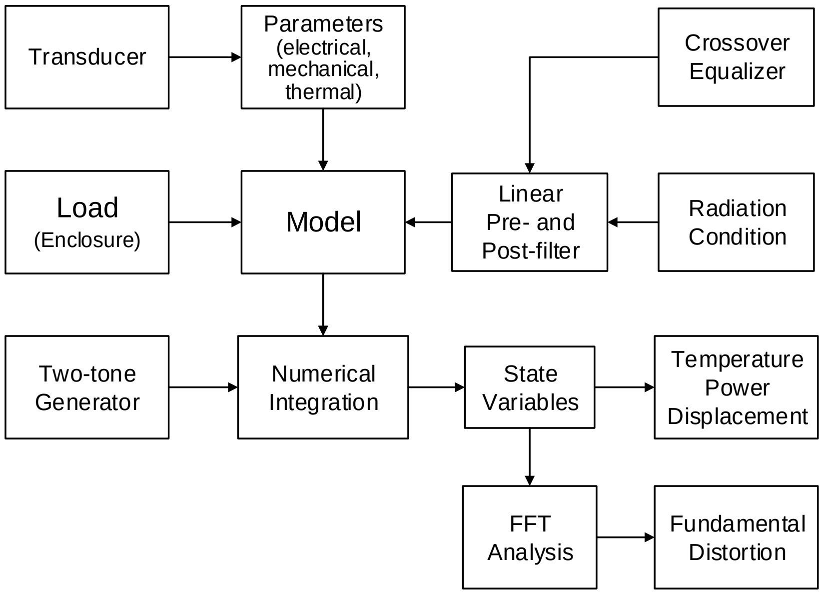

Figure 6: Overview on the large signal simulation of electro-dynamical transducer

Figure 6 shows a signal flow chart of the simulation software using the lumped parameters of the transducer and enclosure as inputs. Linear transfer functions are used for considering a complex load (e.g. a horn) connected to the transducer besides the pre-shaping by an electrical crossover and the post-shaping by sound propagation. The differential equation in Figure 1 is solved by numerical integration in the time domain giving access to all state variables such as displacement, current, sound pressure, voice coil temperature and power as well. A spectral analysis (FFT) applied to the state variables provides the amplitude response of fundamental, dc component, harmonic and intermodulation distortion for a sinusoidal two-tone stimulus.
This tool can be used as an interactive textbook to understand the relationship between loudspeaker nonlinearities and their symptoms.

8 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: The coefficient k_1 in the power series expansion of the stiffness $K_{ms}(x)$ in Equation 1 generates an asymmetrical shape of the stiffness curve and a dc component in the restoring force F as shown in Figure 3. Under which condition does the asymmetrical stiffness produce a dc component in the sound pressure output at a listening position in the far field?

- □ **MC a:** There are no conditions under which we find a dc component in the sound pressure output. The high-pass filter in the linear path in Figure 4 blocks the dc component.
- □ **MC b:** If we find a dc component in the voice coil displacement we will also find a dc component in the sound pressure output.

QUESTION 2: Is it possible to compensate all signal distortion generated by force factor nonlinearities by an appropriately selected curve shape of the stiffness nonlinearity?

- □ **MC a:** Yes, because all important nonlinearities in loudspeakers can be represented by the same generalized model in Figure 5.

- □ **MC b:** No, because the pre-filter $H_{1,1}(f)$ and $H_{1,2}(f)$ in the generalized model in Figure 5 have different frequency responses. Thus, it is only possible to compensate force factor distortion at one particular frequency but not for an ordinary audio signal comprising multiple spectral components.
- □ **MC c:** No, because the stiffness $K_{ms}(x)$ has only one nonlinear effect (restoring force) multiplying the state variable displacement *x* with displacement x, but the force factor *Bl*(*x*) generates two nonlinear effects (damping: multiplying state variable displacement *x* with velocity *v*, and excitation: multiplying the state variable displacement *x* with current *i*).

QUESTION 3: A loudspeaker has only a $K_{ms}(x)$ nonlinearity with a perfectly symmetrical curve shape corresponding to a power series expansion truncated after the quadratic term with ($k_1 = 0$ and $k_2 > 0$). What kind of distortion components are generated in the sound pressure output?

- □ **MC a:** Only 2nd-order harmonic and intermodulation distortion because the $K_{ms}(x)$ contains a quadratic term only.
- □ **MC b:** Only 3rd-order harmonic and intermodulation distortion because the restoring force *F* contains a cubic term of the displacement.
- □ **MC c:** All odd-order harmonic and intermodulation distortion and a nonlinear component at the fundamental frequency because the quadratic term in the power series expansion gives a cubic term in the nonlinear restoring force *F* which generates primarily 3rd-order distortion. However, the further higher-order components (5th, 7th …) are generated by feeding back the distortion to the static nonlinearity and multiplying them with the squared displacement.
- □ **MC d:** All higher order distortion (2nd, 3rd, 4th, 5th …) because the output of the static nonlinearity is feedback to the input.

9 Measurement tasks with database

Step 1: View the demo movie *Predicting the Nonlinear Loudspeaker Behavior* provided at www.klippel.de/training to see how a practical simulation is performed.

Step 2: Run the Software *dB-Lab* and open the file Training 5_*Predicting the Nonlinear Loudspeaker Behavior.kdbx*

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

9.1 Harmonic Distortion Simulations

Step 3: Select the operations ***2a DIS X Fund., DC, Short*** - which shows the measured voice coil displacement versus frequency at four different voltages spaced logarithmically between 1 V and 6 V with a short stimulus – and compare the results windows ***"Peak + Bottom"***, ***"DC Component"***, and ***"Compression"*** with the corresponding result windows in the operation ***2b SIM linear*** – which shows the results of the linear modelling of the voice coil displacement for the same stimulus.

QUESTION 4: What causes the differences between measurements and linear modeling?

- □ **MC a:** The linear model cannot consider the compression of the fundamental component.
- □ **MC b:** The linear model predicts the displacement above resonance frequency too high.
- □ **MC c:** The laser sensor generates a dc displacement in the measured output signal which is not generated by the loudspeaker under test.
- □ **MC d:** The laser sensor limits the peak displacement at low frequencies but the voice coil displacement of the loudspeaker is not affected.
- □ **MC e:** The loudspeaker generates a positive dc displacement in the displacement which is maximal at resonance frequency.

Step 4: Open the result window "***Bl(x)***" in the operation ***2c SIM all nonlinearities***. The black curve ***Covered by SIM*** shows the *Bl* variation during the simulation. Use the cursor to read the minimal *Bl* value generated by the stimulus and calculate the minimal force factor ratio ($Bl_{min} = Bl(x_{peak})/Bl(x = 0)$*100%) according during the simulation!

Step 5: Open the result window "***State***" in operation ***1a LSI Clim 50%*** and compare the Bl_{min} in the measured *Bl*-curve with the Bl_{min} in the simulation.

QUESTION 5: Does the difference between these two values affect the accuracy of the simulation?

- □ **MC a:** Yes, the Bl_{min} ratio in the LSI is larger than the Bl_{min} in the simulation. Thus the maximal peak displacement calculated in SIM is larger than the maximal displacement generated during the nonlinear parameter measurement. The SIM extrapolates the curve shape at higher displacement by using the Taylor series expansion. The user of the SIM has to check the curve shape and to ensure that the extrapolation is meaningful.
- □ **MC b:** No, the Bl_{min} ratio in the LSI is smaller than the Bl_{min} in the simulation and the curve shape of all nonlinearities is correctly identified in displacement range used in the simulation.

Step 6: Compare the result window ***"Peak + Bottom"*** in the operation ***2c SIM all nonlinearities*** with the corresponding curve in the Operation ***2a DIS X Fund., DC, Short***. The agreement between measured and simulated displacement is an important criterion for the accuracy for the nonlinear modelling.

QUESTION 6: Why is the agreement between measured and simulated displacement so important?

- □ **MC a:** The dominant loudspeaker nonlinearities $Bl(x)$, $L(x)$, $K_{ms}(x)$ depend on the voice coil displacement x. A small error in the estimated displacement has a significant influence on the distortion generation process (because there is a nonlinear relationship between input and output of the nonlinearities).
- □ **MC b:** The voice coil displacement may contain the dc component generated by asymmetries in $Bl(x)$, $L(x)$, $K_{ms}(x)$ which shifts the working point dynamically. The dc displacement has a significant influence on the distortion generation process but cannot be detected in the sound pressure measurement.
- □ **MC c:** The absolute measurement of voice coil displacement is a critical criterion for the evaluation of the modeling because this measurement can be performed at a higher accuracy than the absolute measurement of the sound pressure output. Acoustical measurements require careful consideration of the radiation condition (e.g. baffle), sound propagation (e.g. distance) and influence of the acoustical environment (room).

Step 7: Open the operation ***2d SIM Kms(x) only*** - where the nonlinear stiffness $K_{ms}(x)$ is activated but all other nonlinearities are disabled - and compare the curves in the result windows ***"DC Component"*** and ***"Compression"*** with the corresponding curves simulated by ***2c SIM all nonlinearities*** considering the contribution of all nonlinearities and the linear modeling in ***2b SIM linear***.

QUESTION 7: What kind of nonlinear effects found in the simulation ***2c SIM all nonlinearities*** are significantly influenced by $K_{ms}(x)$ nonlinearity?

- □ **MC a:** compression of the fundamental component at resonance frequency (f = 82 Hz)
- □ **MC b:** compression of the fundamental component below resonance frequency (f < 82 Hz)
- □ **MC c:** dc displacement at low frequencies (f < 82 Hz)
- □ **MC d:** dc displacement at the resonance frequency (f = 82 Hz)
- □ **MC e:** dc displacement at high frequencies (f > 200 Hz)

QUESTION 8: The dc offset of the transducer with the nonlinear stiffness as shown in the window ***"Kms(x)"*** in operation ***2d SIM Kms(x) only*** is always positive. What is the reason for this?

- □ **MC a:** The suspension in the particular simulation has a lower stiffness for positive displacement than for negative displacement and generates a positive dc displacement for any AC displacement.
- □ **MC b:** All loudspeaker suspensions generate a positive dc displacement independent of the shape of the nonlinear $K_{ms}(x)$ curve.

Step 8: Compare the result windows ***"Peak + Bottom"***, ***"DC Component"*** and ***"Compression"*** from Operations ***2e SIM Bl(x) only*** and ***2c SIM all nonlinearities*** and the linear modeling in ***2b SIM linear***.

QUESTION 9: What kind of nonlinear effects found in the simulation ***2c SIM all nonlinearities*** are significantly influenced by $Bl(x)$ nonlinearity?

- □ **MC a:** compression of the fundamental component at resonance frequency (f = 82 Hz)
- □ **MC b:** compression of the fundamental component below resonance frequency (f < 82 Hz)
- □ **MC c:** dc displacement at low frequencies (f < 82 Hz)
- □ **MC d:** dc displacement at the resonance frequency (f = 82 Hz)
- □ **MC e:** dc displacement at high frequencies (f > 82 Hz)

Step 9: For a transducer with dominant asymmetry in the *Bl* characteristic the dc component changes the sign at the resonance frequency f_s (here at 82 Hz). Compare the sign of the ***"DC Component"*** with the shape of the $Bl(x)$ curve in the result window ***"Bl(x)"*** in operation ***2e SIM Bl(x) only***.

QUESTION 10: Which property of the dc displacement generated by $Bl(x)$ nonlinearity is correct?

- □ **MC a:** The dc generated at low frequencies ($f < f_s$) shifts the coil away from the *Bl* maximum.
- □ **MC b:** The dc generated at low frequencies ($f < f_s$) shifts the coil towards the *Bl* maximum.
- □ **MC c:** The dc generated at high frequencies ($f > f_s$) shifts the coil away from the *Bl* maximum.
- □ **MC d:** The dc generated at high frequencies ($f > f_s$) shifts the coil towards the *Bl* maximum.
- □ **MC e:** The isolated *Bl(x)* nonlinearity doesn't generate a dc component at resonance frequency f_s (here at 82 Hz).

QUESTION 11: Which explanation for the generation of the dc displacement by force factor nonlinearity is correct?

- □ **MC a:** The dc component is generated by the excitation force $F = Bl(x)i$ where the electrical current i is multiplied with a function of voice coil displacement x. At the resonance frequency there is a 90 degree phase shift between electrical current i and the displacement x and the multiplication produces no dc component in the long-term sense like the correlation of orthogonal signals.
- □ **MC b:** The dc component is generated by the nonlinear damping where the velocity and displacement are multiplied with each other. There is a 90 degree phase shift between velocity and the displacement x and the multiplication produces no dc component like the correlation of orthogonal signals.

Step 10: Open the operation ***2f SIM L(x) only*** and compare the curves ***"DC Component"*** and ***"Compression"*** with the corresponding curves simulated by ***2c SIM all nonlinearities*** considering the contribution of all nonlinearities and the linear modeling in ***2b SIM linear***.

QUESTION 12: What kind of nonlinear effects found in the simulation ***2c SIM all nonlinearities*** are significantly influenced by $L(x)$ nonlinearity and are useful symptoms for loudspeaker diagnostics?

- □ **MC a:** compression of the fundamental component at resonance frequency (f = 82 Hz)
- □ **MC b:** compression of the fundamental component below resonance frequency (f < 82 Hz)
- □ **MC c:** dc displacement at low frequencies (f < 82 Hz)
- □ **MC d:** dc displacement at the resonance frequency (f = 82 Hz)
- □ **MC e:** dc displacement at high frequencies (f > 82 Hz)

Step 11: For a transducer with dominant asymmetry in the inductance $L(x)$ characteristic the dc component has a characteristic frequency response. Compare the sign of the dc with the shape of the $L(x)$ curve in the result window ***"L(x)"*** in operation ***2f SIM L(x) only***.

QUESTION 13: Which explanation(s) is (are) correct?

- □ **MC a:** The dc component generated by the $L(x)$ nonlinearity does not change with frequency.
- □ **MC b:** The dc component generated by the $L(x)$ nonlinearity moves the coil towards the maximum of the inductance.
- □ **MC c:** The dc component generated by the $L(x)$ nonlinearity moves the coil away from the maximum of the inductance curve.
- □ **MC d:** The dc component generated by $L(x)$ nonlinearity has a local minimum at the resonance frequency where the amplitude of the voice coil current is also minimal.
- □ **MC e:** The $L(x)$ nonlinearity generates the largest dc component at the resonance frequency fs.

Step 12: Open the operation ***2g SIM L(i) only*** and compare the curves in the result windows ***"Peak + Bottom"***, ***"DC Component"*** and ***"Compression"*** with the corresponding curves in the operation ***2c SIM all nonlinearities*** and the linear modelling in ***2b SIM linear***.

QUESTION 14: What kind of nonlinear effects found in the simulation ***2c SIM all nonlinearities*** are influenced by $L(i)$ nonlinearity?

- □ **MC a:** compression of the fundamental component at resonance frequency (f = 82 Hz)
- □ **MC b:** compression of the fundamental component below resonance frequency (f < 82 Hz)
- □ **MC c:** dc displacement at low frequencies (f < 82 Hz)
- □ **MC d:** dc displacement at the resonance frequency (f = 82 Hz)
- □ **MC e:** dc displacement at high frequencies (f > 82 Hz)

Step 13: Open the operation ***3a DIS SPL Harmonics*** and compare the curves in the result window ***"Fundamental"*** with the corresponding curves in the operation ***3b SIM all nonlinearities*** considering the contribution of all nonlinearities.

QUESTION 15: What causes the discrepancies between measured and simulated response of the fundamental component?

- □ **MC a:** Break-up modes on the cone at high frequencies are not considered in the simulation. The sound radiation in the simulation is based on a lumped parameter model assuming a rigid cone of surface area S_D.
- □ **MC b:** The peaks and dips found in the measured SPL response cannot be explained by the model because no accurate input parameter is provided for the moving mass M_{ms}.
- □ **MC c:** The peaks and dips found in the measured SPL response cannot be explained by the model because no accurate input parameter is provided for the inductance L_e.

Step 14: Open the result window ***"Fundamental + Harmonics"*** of the operations ***3a DIS SPL Harmonics*** and ***3b SIM all nonlinearities*** and compare the measured and simulated amplitude responses of the *2nd Harmonic* and *3rd Harmonics.*

QUESTION 16: Although there is a good agreement between simulation and measurement at low frequencies (below 150 Hz) there are some discrepancies at higher frequencies. What is (are) the physical cause(s)?

- □ **MC a:** At high frequencies the loudspeaker cone does not vibrate as rigid piston anymore. The break-up modes in the cone generate high local displacement somewhere on the cone which is an additional source of nonlinear distortion which is not considered in the simulation.
- □ **MC b:** The measurement reveals a fundamental response (shown as red curve) which is not flat above 1 kHz but reflects the partial vibration of the cone's surface and the particular radiation condition. This frequency response also affects the mechanical vibration and acoustical radiation of the harmonic components and results in a post-shaping of the distortion components.
- □ **MC c:** The deviation in the 2nd and 3rd order distortion above 200 Hz is caused by measurement noise.
- □ **MC d:** The measurement of the sound pressure response has been performed in the near field of the speaker which is best practice for low frequencies. For high frequencies significant deviations exist between the far field and near field sound pressure due to the complex directivity.

Step 15: In the same operations ***3a DIS SPL Harmonics*** and ***3b SIM all nonlinearities*** open the result window ***"2nd Harmonic,%)"*** showing the 2nd order distortion as relative components and find the frequency range where the *2nd Harmonic* at a stimulus of 6 V is smaller than at a stimulus of 3 V.

QUESTION 17: What causes the decrease of the 2nd-order distortion for rising voltages at lower frequencies ($f < f_s$)?

- □ **MC a:** The 2nd-order distortion is reduced at higher amplitudes because the generated dc displacement (which is positive) shifts the coil to the force factor maximum and reduces the asymmetry of the force factor characteristic dynamically.
- □ **MC b:** The 2nd-order distortion is reduced at higher amplitudes because the generated dc displacement (which is positive) shifts the coil to the softer side of the suspension (see $K_{ms}(x)$ curve in ***1a LSI Clim 50%***) and reduces the asymmetry of the stiffness of the suspension dynamically.
- □ **MC c:** The compression of the fundamental displacement reduces the 2nd-order distortion at higher voltages.

Step 16: Select the operation ***3c SIM Kms(x) only***, open the result window ***"Fundamental + Harmonics"*** and compare the frequency response of the *2nd Harmonic* and *3rd Harmonic* generated by the $K_{ms}(x)$ nonlinearity with the distortion simulated by ***3b SIM all nonlinearities*** considering the contribution of all nonlinearities**.**

QUESTION 18: Is the harmonic distortion above 300 Hz caused by the $K_{ms}(x)$ nonlinearity?

- □ **MC a:** No, the $K_{ms}(x)$ nonlinearity is not the cause of the 2nd-order distortion above 300 Hz because the 2nd-order distortion generated by the $K_{ms}(x)$ decays by approximately 24 dB per octave above resonance frequency.
- □ **MC b:** No, the $K_{ms}(x)$ nonlinearity is not the cause of the 3rd-order distortion above 300 Hz because the 3rd-order distortion generated by the $K_{ms}(x)$ decays by approximately 36 dB per octave above resonance frequency.
- □ **MC c:** Yes, the $K_{ms}(x)$ nonlinearity is the cause of the 2nd-order distortion above 300 Hz because the 2nd-order distortion generated by the $K_{ms}(x)$ is almost constant versus frequency.
- □ **MC d:** Yes, the $K_{ms}(x)$ nonlinearity is the cause of the 3rd-order distortion above 300 Hz because the 3rd-order distortion generated by the $K_{ms}(x)$ is almost constant versus frequency.

Step 17: Select the operation ***3d SIM Bl(x) only***, open the result window ***"Fundamental + Harmonics"*** and compare the frequency response of the *2nd Harmonic* and *3rd Harmonic* generated by the $Bl(x)$ nonlinearity with the harmonic distortion simulated by ***3b SIM all nonlinearities*** considering the contribution of all nonlinearities**.**

QUESTION 19: Is the harmonic distortion above 400 Hz caused by the $Bl(x)$ nonlinearity?

- □ **MC a:** No, the 2nd-order distortion above 400 Hz is not generated by the $Bl(x)$ nonlinearity because it decreases by approximately 12 dB per octave at higher frequencies.
- □ **MC b:** No, the 3rd-order distortion above 400 Hz is not generated by the $Bl(x)$ because it decreases by approximately 24 dB per octave at higher frequencies.
- □ **MC c:** Yes, the 2nd-order distortion above 400 Hz is generated by the $Bl(x)$ nonlinearity because it decreases by approximately 6 dB per octave at higher frequencies.
- □ **MC d:** Yes, the 3rd-order distortion above 400 Hz is generated by the $Bl(x)$ nonlinearity because it decreases by approximately 6 dB per octave at higher frequencies.

Step 18: Select the operation ***3e SIM L(x) only***, open the window ***"Fundamental + Harmonics"*** and compare the frequency response of the *2nd Harmonic* and *3rd Harmonic* generated by the $L(x)$ nonlinearity with the harmonic distortion simulated by ***3b SIM all nonlinearities*** considering the contribution of all nonlinearities**.**

QUESTION 20: What does the comparison reveal?

- □ **MC a:** The 2nd-order harmonic distortion generated by the $L(x)$ nonlinearity is maximal above the resonance frequency (f_s) but decreases slowly by approximately 3 dB per octave to higher frequencies. Those kinds of distortions are mostly generated by the reluctance force which is proportional to the squared electrical input current.
- □ **MC b:** The 3rd-order harmonic distortion generated by the $L(x)$ is very small (>50 dB below the fundamental) and negligible.
- □ **MC c:** The $L(x)$ nonlinearity of the transducer under test is not a dominant source of 2nd-order harmonic distortion.

Step 19: Select the operation ***3f SIM L(i) only***, open the result window ***"Fundamental + Harmonics"*** and compare the frequency response of the *2nd Harmonic* and *3rd Harmonic* generated by the $L(i)$ nonlinearity with the harmonic distortion simulated by ***3b SIM all nonlinearities*** considering the contribution of all nonlinearities and the linear modelling in ***2b SIM linear***.

QUESTION 21: What does the comparison reveal?

- □ **MC a:** The 2nd-order distortion generated by the $L(i)$ nonlinearity are almost constant at higher frequencies.
- □ **MC b:** The harmonic distortion generated by the $L(i)$ nonlinearity are negligible at low frequencies below resonance frequency.
- □ **MC c:** The harmonic distortion generated by $L(i)$ is higher than the harmonic distortion generated by $Bl(x)$ and $K_{ms}(x)$ at high frequencies ($f > 5f_s$).
- □ **MC d:** The harmonic distortion generated by $L(i)$ fall by 12 dB per octave above resonance frequency.

Step 20: Select the operation ***3g SIM Doppler only*** and compare the result windows ***"Fundamental + Harmonics"*** and ***"Compression"*** with the corresponding nonlinear symptoms of the simulation ***3b SIM all nonlinearities*** considering the contribution of all nonlinearities.

QUESTION 22: What does the comparison reveal?

- □ **MC a:** The Doppler Effect produces small 2nd order harmonic distortion.
- □ **MC b:** The 3rd order harmonic generated by the Doppler Effect is negligible.
- □ **MC c:** Doppler Effect generates no compression of the fundamental.

Step 21: Compare the 2nd-order harmonic distortion at resonance frequency ($f_s = 82$ Hz) in the result window ***2nd Harmonic, %*** of simulations ***3b-3g*** summarized in the object ***3j SIM comparison***.

QUESTION 23: What is (are) the dominant cause(s) of the 2nd-order harmonic distortion at resonance which may be used as a general symptom for loudspeaker diagnostics?

- □ **MC a:** Stiffness $K_{ms}(x)$
- □ **MC b:** Force factor $Bl(x)$
- □ **MC c:** Inductance $L(x)$
- □ **MC d:** Inductance $L(i)$
- □ **MC e:** Doppler Effect

Step 22: Compare the 3rd-order harmonic distortion in the result window ***"3rd Harmonics, %"*** in simulations ***3b-3g*** at resonance frequency ($f_s = 82$ Hz) considering each nonlinearity separately. The calculated distortion curves are copied into object ***3j SIM comparison*** to simplify the comparison.

QUESTION 24: What is (are) the dominant cause(s) of the 3rd-order harmonic distortion at resonance which may be used as a general symptom for loudspeaker diagnostics?

- □ **MC a:** Stiffness $K_{ms}(x)$
- □ **MC b:** Force factor $Bl(x)$
- □ **MC c:** Inductance $L(x)$
- □ **MC d:** Inductance $L(i)$
- □ **MC e:** Doppler Effect

9.2 Intermodulation Distortion Simulations

Step 23: Open the result window ***"2nd Intermod, %"*** in operation ***4a DIS SPL IMD (bass sweep)*** and compare the 2nd-order intermodulation distortion with the results of the simulation ***4b SIM all nonlinearities*** considering the contribution of all nonlinearities.

Step 24: Inspect the 2nd-order intermodulation distortion in the result window ***"2nd Intermod, %"*** in operations ***4c–4g*** considering each nonlinearity separately. The distortion curves are copied into operation ***4i SIM comparison*** to simplify the comparison.

QUESTION 25: Which nonlinearity contributes significantly to the 2nd-order intermodulation distortion which may be used as a general symptom for loudspeaker diagnostics?

- □ **MC a:** Stiffness $K_{ms}(x)$
- □ **MC b:** Force factor $Bl(x)$
- □ **MC c:** Inductance $L(x)$
- □ **MC d:** Inductance $L(i)$
- □ **MC e:** Doppler Effect

Step 25: Inspect the 3rd-order intermodulation distortion in the result window ***"3rd, Intermod, %"*** in operations ***4c–4g*** considering each nonlinearity separately. The calculated distortion curves are copied into operation ***4i SIM comparison*** to simplify the comparison.

QUESTION 26: Which nonlinearity contributes significantly to the 3rd-order intermodulation distortion which may be used as a general symptom for loudspeaker diagnostics?

- □ **MC a:** Stiffness $K_{ms}(x)$
- □ **MC b:** Force factor $Bl(x)$
- □ **MC c:** Inductance $L(x)$
- □ **MC d:** Inductance $L(i)$
- □ **MC e:** Doppler Effect

QUESTION 27: Why are the intermodulation distortions generated by the $K_{ms}(x)$ nonlinearity small?

- □ **MC a:** The intermodulation distortion measurement uses a two-tone signal. The low-frequency tone f_1 generates sufficient displacement for $f_1 < f_s$ and causes significant variation of the nonlinear stiffness $K_{ms}(x)$ and harmonics of f_1. However, the high-frequency tone $f_2 = 900$ Hz generates only low displacement and cannot produce significant intermodulation components.
- □ **MC b:** The transducer in ***1a LSI Clim 50%*** has a relatively linear stiffness and produces low distortion.

Step 26: Compare the distortion in result window ***"3rd Intermod, %"*** in operations ***4d SIM Bl(x) only*** neglecting the nonlinear suspension with the corresponding distortion in operations ***4h SIM Kms(x)+Bl(x) only*** considering the suspension nonlinearity.

QUESTION 28: Why does the $K_{ms}(x)$ nonlinearity reduce the generation of the intermodulation distortion?

- □ **MC a:** The nonlinear stiffness $K_{ms}(x)$ causes a compression of the fundamental component in voice coil displacement. If the displacement is reduced the $Bl(x)$ nonlinearity generates less intermodulation distortion.
- □ **MC b:** The intermodulation distortion generated by $K_{ms}(x)$ compensates for the $Bl(x)$ distortion.

Step 27: Compare the intermodulation distortion in ***4e SIM L(x) only*** and ***4f SIM L(i) only***.

QUESTION 29: What causes the differences in the intermodulation distortion generated by $L(x)$ and $L(i)$?

- □ **MC a:** The intermodulation distortion generated by $L(i)$ have a local minimum when the bass tone f_1 excites the transducer at the resonance frequency (f_s = 82 Hz) where voice coil current is minimal and the electrical input impedance is maximal.
- □ **MC b:** The intermodulation distortion generated by $L(x)$ nonlinearity depends on the voice coil displacement and vanishes when the bass tone f_1 has passed the resonance frequency f_s and produces less displacement.

Step 28: Open the operation ***5a DIS CURRENT IMD (bass sweep)*** and ***5b SIM all nonlinearities***. Compare the measured and simulated intermodulation distortion in result windows ***"2nd Intermod, %"*** found in the electrical input current. Inspect the contribution of each nonlinearity in following simulation ***5b-5g*** considering each nonlinearity separately. The calculated distortion curves are copied into operation ***5i SIM comparison*** to simplify the comparison.

QUESTION 30: Which nonlinearity contributes significantly to the 2^{nd}-order intermodulation distortion in the input current which may be used as a general symptom for loudspeaker diagnostics?

- □ **MC a:** Stiffness $K_{ms}(x)$
- □ **MC b:** Force factor $Bl(x)$
- □ **MC c:** Inductance $L(x)$
- □ **MC d:** Inductance $L(i)$
- □ **MC e:** Doppler Effect

Step 29: Select operations ***6a DIS SPL IMD (voice sweep)*** and ***6b SIM all nonlinearities*** generated in the sound pressure output by using a bass tone at fixed frequency f_2 = 20 Hz and a voice tone f_1 > 400 Hz. Compare the measured and simulated 2^{nd}-order and 3^{rd}-order intermodulation distortion in the result window ***"2nd Intermod, %"*** and ***"3rd Intermod, %"***. There is a good agreement over a wide frequency range but the measurement reveals much more intermodulation distortion at a particular frequency, 1.9 kHz, which is not predicted by the simulation. Open operation ***1b Linear parameter Measurement*** and view the impedance response at 1.9 kHz in result window ***"Impedance Magnitude"***. Open operation ***1c CAL Scanner Result*** and open the result Curve 1 showing the SPL Decomposition. View the curve *Acceleration Level* and *Anti Phase component* at 1.9 kHz.

QUESTION 31: Which loudspeaker nonlinearities can cause this kind of distortion?

- □ **MC a:** The first natural frequency of a break-up mode on the cone is not considered in the simulation. The cone-surround system breaks up at 1.9 kHz and there is a first maximum in the total acceleration level and a significant increase of the Anti-Phase Component. This mode also generates a small peak in the electrical input impedance. However, this natural frequency of this mode depends on the voice coil displacement generated by the bass tone f_2. The variation of the mode causes an intermodulation of the voice tone f_1.
- □ **MC b:** Insufficient modelling of the inductance nonlinearity $L(x)$.
- □ **MC c:** Insufficient modelling of the Doppler distortion.

Step 30: Compare the distortion in result window ***"2nd Intermod, %"*** of ***6b SIM all nonlinearities*** with the simulated distortion generated by separated nonlinearities as shown in operation ***6c-6g***. The calculated distortion curves are copied into operation ***6i SIM comparison*** to simplify the comparison.

QUESTION 32: Which nonlinearity contributes significantly to the 2nd-order intermodulation distortion which may be used as a general symptom for loudspeaker diagnostics?

- □ **MC a:** Stiffness $K_{ms}(x)$
- □ **MC b:** Force factor $Bl(x)$
- □ **MC c:** Inductance $L(x)$
- □ **MC d:** Inductance $L(i)$
- □ **MC e:** Doppler Effect

Step 31: View the frequency response of the 2nd-order and 3rd-order intermodulation distortion in the operation ***6c SIM Kms(x) only*** considering the stiffness nonlinearity only.

QUESTION 33: Why do the intermodulation distortions generated by $K_{ms}(x)$ decay with frequency f_1?

- □ **MC a:** The nonlinear restoring force $F_r = K_{ms}(x)x$ depends on displacement x only. While the bass tone $f_2 = 20$ Hz generates high variation of the stiffness $K_{ms}(x)$ the displacement of the voice tone decreases by 12 dB per octave to higher frequencies.
- □ **MC b:** The electrical input impedance rises to higher frequencies and reduces the input current at higher frequencies.

Step 32: View the frequency response of the 2nd-order and 3rd-order intermodulation distortion in the operation ***6d SIM Bl(x) only*** considering the force factor nonlinearity only.

QUESTION 34: Why is the magnitude of the intermodulation distortions generated by force factor nonlinearity Bl(x) independent of the frequency of voice tone f_1?

- □ **MC a:** The intermodulation distortions are generated by the electro-dynamical driving force $F = Bl(x)i$ which depends on displacement x and current i. The bass tone $f_2 = 20$ Hz generates the displacement x, which varies the force factor $Bl(x)$ and modulates the electrical input current i. Since the voice tone generates high values of current i at higher frequencies $f_1 > f_s$, the intermodulation distortions are almost independent of the frequency f_1.
- □ **MC b:** The intermodulation distortions are generated by the nonlinear damping force $F = (Bl(x))^2 * v/R_e$ which is a second nonlinear effect of $Bl(x)$-nonlinearity which depends on displacement x and velocity v. The velocity and displacement are constant at higher frequencies ($f >> f_s$).

Step 33: Compare the distortion in result window ***"3rd Intermod, %"*** of ***6b SIM all nonlinearities*** with the simulated distortion generated by separated nonlinearities as shown in operation ***6c-6g***. The calculated distortion curves are copied into operation ***6i SIM comparison*** to simplify the comparison.

QUESTION 35: Which nonlinearity contributes significantly to the 3rd-order intermodulation distortion at higher frequencies ($f >> f_s$) which may be used as a general symptom for loudspeaker diagnostics?

- □ **MC a:** Stiffness $K_{ms}(x)$
- □ **MC b:** Force factor $Bl(x)$
- □ **MC c:** Inductance $L(x)$
- □ **MC d:** Inductance $L(i)$
- □ **MC e:** Doppler Effect

Step 34: Compare the 2nd-order and 3rd-order intermodulation distortion in ***6c SIM Kms(x) only*** and ***6d SIM Bl(x) only*** with the intermodulation distortion generated by ***6h SIM Kms(x) + Bl(x) only*** considering the interaction of $Bl(x)$ and $K_{ms}(x)$ nonlinearity.

QUESTION 36: What causes the increase of the 2nd-order distortion when the $K_{ms}(x)$ nonlinearity is considered?

- □ **MC a:** The asymmetry of the $K_{ms}(x)$ nonlinearity generates a dc component in the voice coil displacement which is obvious in the peak values x_{peak} = 2.5 mm which is higher than the negative bottom value x_{bottom} = -2.2 mm of the black curve *Covered by SIM* in the result window *"**Bl(x)**"* of operation ***6h SIM Kms(x) + Bl(x) only***. This dc displacement shifts the working point in the $Bl(x)$ curve and increases the force factor asymmetry dynamically resulting in higher values of 2nd-order intermodulation distortion.
- □ **MC b:** The asymmetry of the $K_{ms}(x)$ generates 2nd-order intermodulation distortion which has the opposite phase to the 2nd-order intermodulation distortion generated by $Bl(x)$ giving less distortion in total.

QUESTION 37: What causes the decrease of the 3rd-order distortion when the $K_{ms}(x)$ nonlinearity is considered?

- □ **MC a:** The $K_{ms}(x)$ generates 3rd-order intermodulation distortion which has the opposite phase to the 3rd-order intermodulation distortion generated by $Bl(x)$ giving less distortion in total.
- □ **MC b:** The $K_{ms}(x)$ nonlinearity reduces the peak and bottom displacement as obvious in the window "***Bl(x)***" of operation ***6h SIM Kms(x) + Bl(x) only***. The reduced fundamental displacement will cause less nonlinear variation of the force factor $Bl(x)$ and produce less 3rd-order intermodulation distortion.

Step 35: Compare the 2nd-order intermodulation distortion measured in electrical input current by using a varying high-frequency tone 400 Hz < f_1 < 3 kHz in measurement 7***a DIS CURRENT IMD (voice sweep)*** with the simulated distortion considering all nonlinearities ***7b SIM all nonlinearities*** and separated nonlinearities ***7c-7g***. The calculated distortion curves are copied into object ***7i SIM comparison*** to simplify the comparison.

QUESTION 38: Which nonlinearity contributes significantly to the 2nd-order intermodulation distortion which may be used as a general symptom for loudspeaker diagnostics?

- □ **MC a:** Stiffness $K_{ms}(x)$
- □ **MC b:** Force factor $Bl(x)$
- □ **MC c:** Inductance $L(x)$
- □ **MC d:** Inductance $L(i)$
- □ **MC e:** Doppler Effect

10 Performing Measurements

If the KLIPPEL measurement system is available it is recommended to investigate a real transducer with a resonance frequency $f_s < 200$ Hz (woofer). However, this part is optionally and is focused on measurement and simulations to develop practical skills and experiences.

10.1 Measurement of Nonlinear Parameters (LSI)

Later on, the SIM operations require linear, nonlinear and thermal parameters. These can be measured with and imported from an LSI operation.
Use the provided data in measurement object *8 Exercise* or perform a measurement on a loudspeaker.

Step 36: Run the LSI measurement to measure the linear and nonlinear parameters of the transducer.

10.2 Measurement of DC displacement (DIS)

The simulation module SIM and the measurement module DIS use the same stimulus and perform the same signal analysis of the predicted and measured data, respectively. This simplifies the evaluation of the simulation.
Use the provided data in measurement object *8 Exercise* or perform a measurement on a loudspeaker

Step 37: Create a new DIS operation by using the template *DIS X fundamental, DC*.

Step 38: Open property page *Stimulus* and select *Harmonics* in *Mode* and specify the frequency and voltage considering the particularities of the transducer.

Step 39: Open property page *Protection*. Disable *Voice coil temperature Monitoring*.

Step 40: Open property page *Input*. Select *X (Displacement)* in group *Y2 (Channel 2)* and *Off* in group *Y1 (Channel 1)*.

Step 41: Open property page *Display*. Select *Displacement X* in *State signal* and *2D plot versus f1* in group Plot style.

Step 42: Run the DIS Measurement.

10.3 Simulate all nonlinearities

Step 43: Create a new operation SIM by pressing *New operation* in the dB-Lab toolbar. Rename this operation “*SIM All Nonlinearities*”.

Step 44: Open property page *Im/Export* in the LSI and press *Export to clipboard*. Open property page *Im/Export* in the SIM and press *Import from clipboard.*

Step 45: Open property page *Im/Export* in the DIS measurement operation *3a DIS X Fundamental, DC* and press *Export to clipboard* to export the measurement setup (e.g. frequency points) from the DIS measurement to the clipboard. Open the property page *Im/Export* in the SIM and press *Import fom clipboard*.

Step 46: In property page *Transducer* enable all nonlinearities by setting all checkboxes.

Step 47: Start the SIM operation and compare the predicted and measured curves in the window *DC Component*. If no dc component is displayed, open property page *Display* and select *X – cone displacement* at parameter *State signal*.

10.4 Simulate only one nonlinearity

Step 48: Duplicate the previous SIM operation by pressing the *Duplicate* button in the dB-lab toolbar or use the menu. Rename the operation (e.g. *SIM Bl(x) only*). Open the property page *Transducer* and enable only one checkbox (e.g. *Bl*(*x*)) and disable all other checkboxes to investigate the effect of one nonlinearity. Start the SIM operation and compare the dc displacement considering a single nonlinearity with the dc displacement in operation *SIM All nonlinearities*.

Step 49: Repeat the last step for other nonlinearities (e.g. stiffness $K_{ms}(x)$). Investigate which nonlinearity generates the largest contribution to the dc displacement.

10.5 Simulate without *Bl* offset

The *Bl* asymmetry is caused by the rest position of the voice coil and by the magnetic field. The simulation tool SIM makes it possible to generate an improved virtual transducer having the voice coil at the optimal rest position.

Step 50: Duplicate the operation the operation "*SIM All Nonlinearities*" and rename this operation *"SIM Coil offset compensated*"

Step 51: Save the original shape of the *Bl*(*x*)-curve by copy and paste to the same window (or select duplicate curve in the right mouse menu).

Step 52: Open the property page *Transducer* and put the cursor on the nonlinear parameter *Bl*(*x*) close to the checkbox. Press the button *Edit curve* and select the editor page *REGULAR*. In section Shift, press the button *Center* and see the value of the voice coil shift in mm.

Step 53: Start the simulation and compare dc component generated by virtual transducer *"SIM Coil offset compensated*" with the dc component of the original transducer "*SIM All Nonlinearities"*.

Step 54: Compare the dc displacement in the simulation *"SIM Coil offset compensated*" with the predicted dc displacement in the simulations considering one nonlinearity only (e.g. *SIM Kms(x) only*). Which nonlinearity provides the highest contribution to the dc displacement in the virtual loudspeaker having the voice coil at the optimal rest position.

10.6 Root Cause Analysis

The simulation tool SIM is perfectly suited to root cause nonlinear symptoms. *8 Exercise* shows a comprehensive measurement object for analysis. When working through the steps please always verify that the simulation is valid, by checking that the amplitude of the peak/bottom waveform of the simulation matches the peak/bottom amplitude of the measurement.

Step 55: Open Measurement Operation *8 Exercise – 3a DIS X Fundamental, DC* and find out, what is the dominant cause for dc generation below resonance frequency, at resonance frequency and above resonance frequency

Step 56: Open Measurement Operation *8 Exercise – 4b DIS SPL Harmonics* and find out, what is the dominant cause for generation of 2nd order harmonic distortion

Step 57: Open Measurement Operation *8 Exercise – 4b DIS SPL Harmonics* and find out, what is the dominant cause for generation of 3rd order harmonic distortion

Step 58: Open Measurement Operation *8 Exercise – 4c DIS IM Dist. (bass sweep) P* and find out, what is the dominant cause for generation of 2nd order Intermodulation Distortion

Step 59: Open Measurement Operation *8 Exercise – 4c DIS IM Dist. (bass sweep) P* and find out, what is the dominant cause for generation of 3rd order Intermodulation Distortion

Step 60: Open Measurement Operation *8 Exercise – 4e DIS IM Dist. (voice sweep) P* and find out, what is the dominant cause for generation of 2nd order Intermodulation Distortion

Step 61: Open Measurement Operation *8 Exercise – 4e DIS IM Dist. (voice sweep) P* and find out, what is the dominant cause for generation of 3rd order Intermodulation Distortion

11 Further Literature

User Manual for the KLIPPEL R&D SYSTEM – *Simulation 2*

User Manual for the KLIPPEL R&D SYSTEM – *Transfer Function*

User Manual for the KLIPPEL R&D SYSTEM – *3D Distortion Measurement*

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

Specification S3 *Simulation Version 2* (SIM):

http://www.klippel.de/fileadmin/klippel/Bilder/Our_Products/R-D_System/PDF/S3_SIM_Version_%202.pdf

Paper *Prediction of Speaker Performance at High Amplitudes*:

http://www.klippel.de/fileadmin/klippel/Files/Know_How/Literature/Papers/Prediction_of_speaker_performance_at_high_amplitudes_01.pdf

Application Note AN 21 Reduce distortion by shifting Voice Coil:

http://www.klippel.de/fileadmin/klippel/Files/Know_How/Application_Notes/AN_21_Bl_Shift.pdf