Linear Lumped Parameter Measurement

The first training will focus on understanding the physical mechanisms in electro-dynamical transducers and applying lumped parameter modelling. The objectives of the hands-on training unit **Linear Lumped Parameter Measurement** are

- Understanding physical mechanisms of electro-dynamic transducers
- Applying lumped parameter modeling
- Measuring lumped parameters using both conventional and new techniques
- Developing skills and experiments in performing practical measurements
- Interpreting measurement results
- Detecting and avoiding measurement errors

Agenda

1. Requirements

1.1 Previous Knowledge of the Participants

This first hands-on training was developed for both electrical or mechanical engineering students and engineers with experience in the electro-acoustical industry.

1.2 Minimum Requirements

Participants will need the results of the measurement provided in a Klippel database *Linear Lumped Parameter Measurement.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.

1.3 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:

- Linear Parameter Measurement Module (LPM)
- Distortion Analyzer DA2
- Laser Sensor + Controller
- Amplifier
- Driver Stand

2. 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 www.klippel.de/training.
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.

3. Theoretical Introduction

This section summarizes the basics of lumped parameter modeling. This information is necessary to accomplish the experimental tasks of this training. The figure below shows the sectional view of a common electro-dynamical transducer used as a woofer in loudspeaker systems.

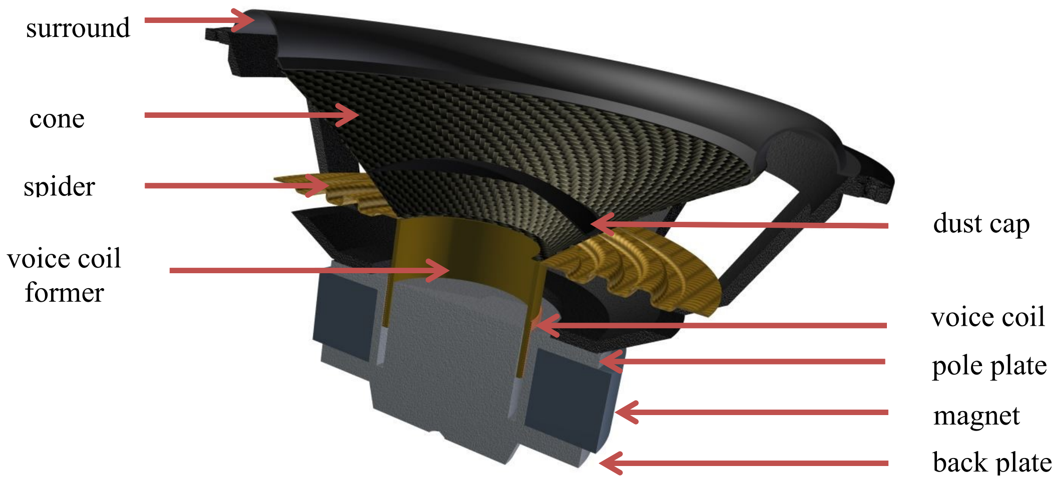
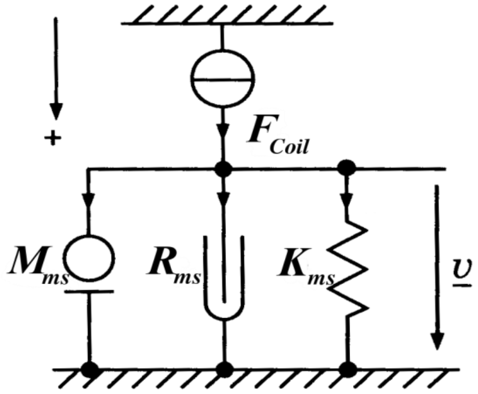


Figure 1: Sectional view of an electro-dynamical transducer (Figure provided by: Isophon GmbH)

3.1 Mechanical modeling at low frequencies

At low frequencies, the wavelength is much larger than the geometrical dimensions of the transducer. The mechanical system may be modeled by lumped parameters forming a damped mass-spring-resonator. See Figure 2 below.



$$\underline{F}_{coil} = \underline{F}_R + \underline{F}_M + \underline{F}_K$$

Figure 2: Mechanical scheme of a loudspeaker

The mass of cone, dust cap, voice coil, voice coil former and the moving part of the mechanical suspension (spider and surround) are summarized in a point mass M_{ms}. This generates an inertia $\underline{F}_M$ proportional to the acceleration *a*, the second derivative of the displacement *x*. The displacement *x* of the voice coil also causes a deformation of the suspension and generates a restoring force $\underline{F}_K$. This drives the coil back to the rest position x=0. In the small signal domain, the force-deflection curve can be approximated by a line where the slope corresponds with the stiffness K_{ms} of the suspension. The mechanical resistance R_{ms} causes a damping force $\underline{F}_R$ proportional to the velocity v and a quadrature component to the other forces $\underline{F}_M$ and $\underline{F}_K$.

Table 1: Overview of mechanical forces

Forces	Physical parts of the transducer	Basic relationship
Total driving force $\underline{F}_{Coil}$	Voice coil + magnet system	$\underline{F}_{coil} = \underline{F}_R + \underline{F}_M + \underline{F}_K$
Friction force $\underline{F}_R$	Friction losses in the mechanical and acoustical elements	$\underline{F}_R = R_{ms} \cdot \underline{v}$ Mechanical resistance R_{ms}, velocity $\underline{v}$
Inertia $\underline{F}_M$	Moving mass: cone, surround, voice coil, spider, coil former, moving air	$\underline{F}_M = M_{ms} \cdot \underline{a} = M_{ms} \cdot j2\pi f \underline{v}$ moving mass M_{ms}, acceleration $\underline{a}$, frequency f and complex operator $j = \sqrt{-1}$
Restoring force $\underline{F}_K$	Deformation of spider and surround	$\underline{F}_K = K_{ms} \cdot \underline{x} = K_{ms} \cdot \frac{\underline{v}}{j2\pi f}$ stiffness K_{ms}, displacement $\underline{x}$

The mechanical admittance $\underline{H}_{mech}(f) = \underline{v} / \underline{F}_{coil}$ describes the complex ratio of velocity $\underline{v}$ and total driving force $\underline{F}_{coil}$. It is a function of frequency and becomes maximal at the resonance frequency

$$f_s = \frac{1}{2\pi}\sqrt{\frac{K_{ms}}{M_{ms}}}$$

where the sum of the restoring force and inertia $\underline{F}_K + \underline{F}_M = 0$. Table 2 summarizes the relationship between frequency and mechanical admittance.

Table 2: Frequency Dependency of the Mechanical Admittance

Frequency Range	Mechanical Impedance	Dominant Force
$f << f_s$	$\underline{H}_{mech}(f) \approx \frac{j2\pi f}{K_{ms}}$ (Stiffness is dominant)	$\underline{F}_{coil} \approx \underline{F}_K$ (driving force equals restoring force)
$f = f_s$ (resonance frequency)	$\underline{H}_{mech}(f) = \frac{1}{R_{ms}}$ (Resistance is dominant)	$\underline{F}_{coil} = \underline{F}_R$, (driving force compensates friction losses)
$f >> f_s$	$\underline{H}_{mech}(f) \approx \frac{1}{j2\pi f M_{ms}}$ (Moving mass is dominant)	$\underline{F}_{coil} \approx \underline{F}_M$ (driving force equals inertia)

3.2 Electro-dynamical Principle

A transducer using the electro-dynamical principle generates a Lorentz force $F_{coil}=Bli$ perpendicular to the surface caused by the magnetic flux density (induction B) and the electrical current i in the wire with the length l. At the same time, the velocity of the voice coil generates a back EMF (Electro Motive Force) Blv. In this way, the electro-dynamic transduction can be represented as a transformer with the coupling constant Bl. See Figure 3.

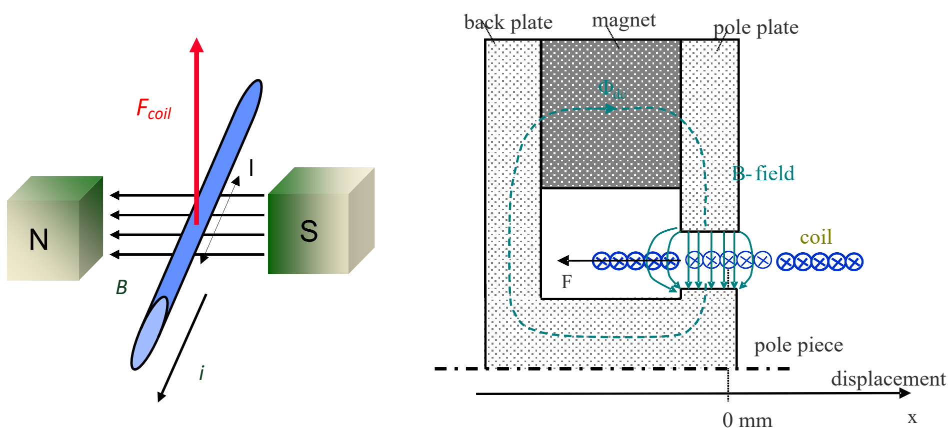


Figure 3: Electro-dynamical transduction principle

The equivalent network to the right in Figure 4 corresponds with the mechanical scheme shown in Figure 2. The left side represents the electrical properties of the voice coil which are discussed in the electrical input impedance $\underline{Z}_e(f)$ section that follows

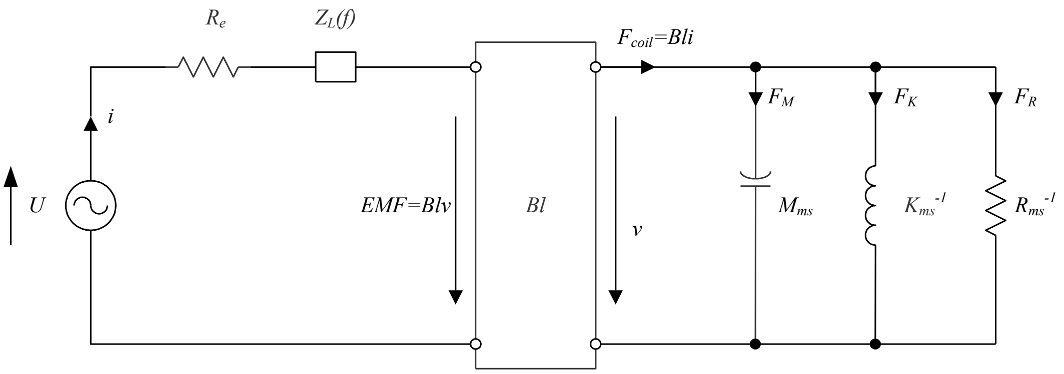


Figure 4: Electro-mechanical equivalent circuit of the electro-dynamical transducer

3.3 Electrical input impedance

The electrical input impedance $\underline{Z}_e(f)$ is the complex ratio of the electrical voltage $\underline{u}$ and the input current i at the terminals. The magnitude response $|\underline{Z}_e(f)|$ (shown in Figure 5) reveals a typical resonance peak at f_s which is directly related to the increase of the mechanical admittance seen from the electrical side.

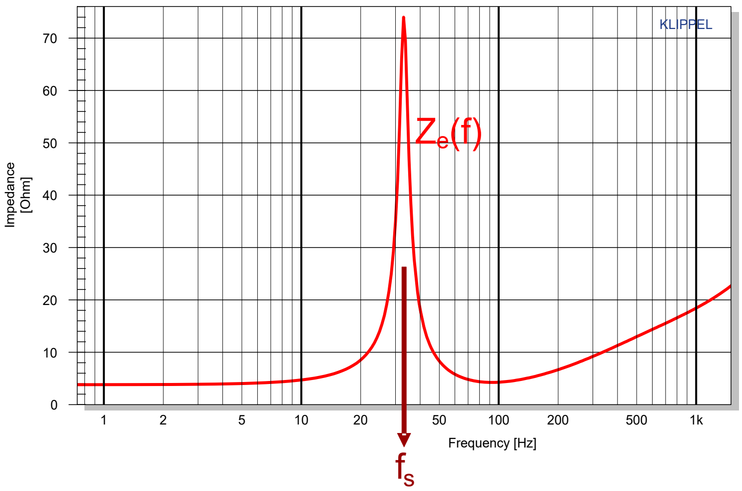


Figure 5: Measured magnitude of electrical impedance versus frequency *f*

At low frequencies where the velocity v is negligible, the magnitude response $|\underline{Z}_e(f)|$ is identical to the electrical dc resistance R_e of the voice coil. However, at higher frequencies $f >> f_s$, the inductance of the voice coil and additional losses caused by eddy currents in the pole tips generate an additional increase of $|\underline{Z}_e(f)|$.

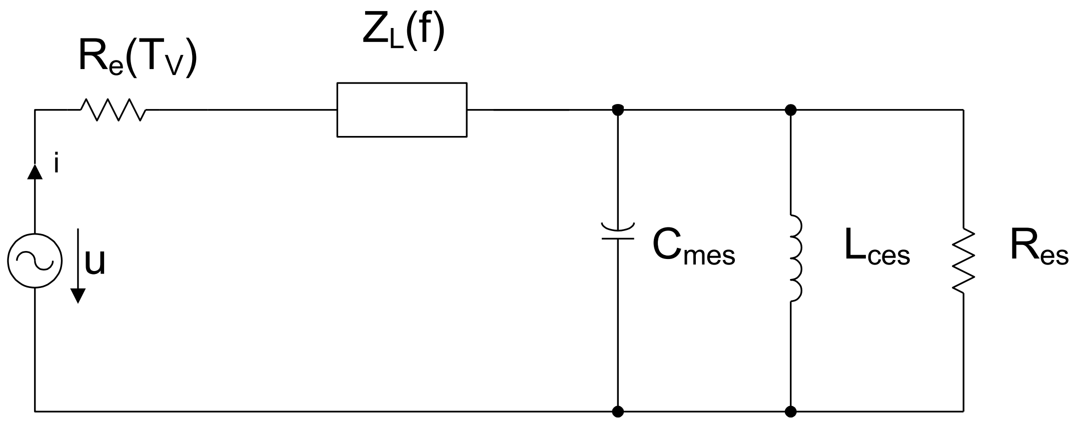


Figure 6: Electrical equivalent circuit

Figure 6 shows how the electrical input impedance $\underline{Z}_e(f)$ can be modeled by an equivalent circuit Figure 6 comprising the electrical parameters defined in Table 3.

Table 3: Basic parameters of the electrical equivalent circuit

R_e	DC voice coil resistance	$R_e = \left\|\underline{Z}_e(f=0)\right\|$
$\underline{Z}_L(f)$	electrical impedance describing lossy inductance of the voice coil with different inductance models (Leach, LR2, Wright, …).	Approximation $\|\underline{Z}_L(f)\| \approx L_e j2\pi f$
C_{mes}	electrical capacity representing moving mass M_{ms}	$C_{mes} = \frac{M_{ms}}{(Bl)^2}$
L_{ces}	electrical inductance representing mechanical compliance C_{ms}	$L_{ces} = C_{ms}(Bl)^2$
R_{es}	electrical resistance representing to mechanical friction losses R_{ms}	$R_{es} = \frac{(Bl)^2}{R_{ms}}$

These variables derive some important parameters as shown in Table 4.

Table 4: Important relative parameters derived from the basic variables

f_s	resonance frequency of the mechanical mass-spring-system (spring force $\underline{F_K}$ equals inertia force $\underline{F_M}$)	$f_s = \frac{1}{2\pi}\sqrt{\frac{1}{C_{mes}L_{ces}}}$
Q_{es}	electrical quality factor representing the electrical damping of the resonance circuit	$Q_{es} = 2\pi f_s C_{mes} R_e$
Q_{ms}	mechanical quality factor representing the mechanical friction losses only	$Q_{ms} = 2\pi f_s C_{mes} R_{es}$
Q_{ts}	total quality factor considering mechanical and electrical losses	$Q_{ts} = \frac{Q_{ms}Q_{es}}{Q_{ms}+Q_{es}}$

4. Parameter Identification

Applying the general transducer model to a particular transducer, the free lumped parameters have to be estimated by minimizing a cost function describing the deviation between estimated and measured behavior.

4.1 Measurement of Electrical Impedance

The electrical impedance $\underline{Z}_e(f)$ measured at the transducer terminals is the basis for estimating the electrical parameters listed in Table 3 and Table 4. Any stimulus providing sufficient excitation of the loudspeaker can be used to measure terminal voltage (input signal) and the electrical current (output signal) of the loudspeaker connected to a power amplifier having low output impedance (voltage drive). The electrical impedance is a linear transfer function and requires that the nonlinear distortion generated by the loudspeaker is negligible. This requires low amplitude of the stimulus while ensuring sufficient signal to noise ratio.
A convenient stimulus is a sparse multi-tone complex to measure the electrical impedance at discrete frequencies spaced logarithmically. Concentrating the spectral power of the stimulus to 16 – 30 lines per octave improves the signal-to-noise ratio, while providing sufficient resolution of the impedance curve to identify the parameters reliably.
The blue lines in Figure 7 represent the fundamental components of the multi-tone spectrum in the measured terminal voltage. The spectral components between the excited frequency lines represented as a grey line reveal the measurement noise and distortion. The noise level measured without stimulus and depicted as black lines agrees with the grey line and indicates that the power amplifier produces very low nonlinear distortion in the voltage signal. Reliable measurement of the impedance requires a signal-to-noise ratio SNR > 40 dB in the voltage signal. Averaging the measured signal by factor N improves the signal to noise ratio by:

$$\Delta SNR = 3\log_2(N) dB$$

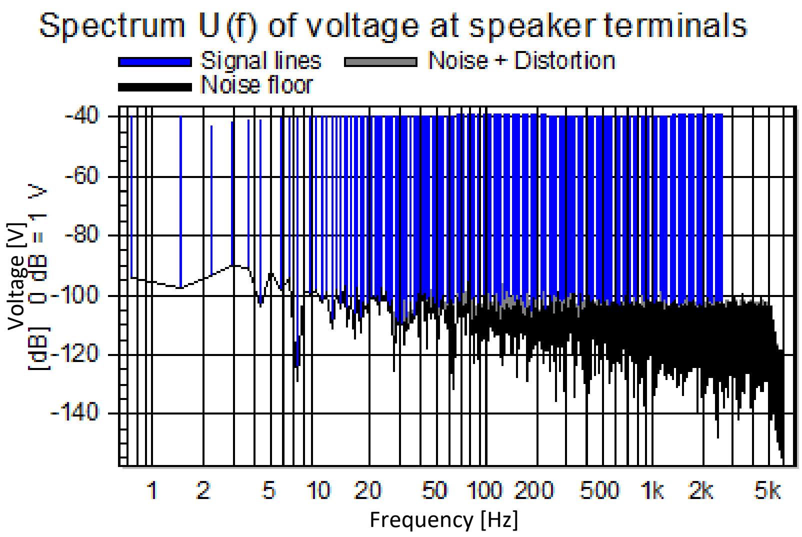


Figure 7: Measured voltage spectrum using a multi-tone stimulus

Figure 8 shows the measured current spectrum of the current signal where fundamental components (red lines) show a characteristic dip at the resonance frequency f_s corresponding with the peak in the impedance curve in Figure 5. The noise and distortion depicted as a grey lines exceed the noise floor shown as black lines at the resonance frequency (here about 120 Hz), indicating the nonlinear behavior of the loudspeaker. However, the signal-to-noise ratio is larger than 30 dB, which is a useful limit ensuring reliable results.

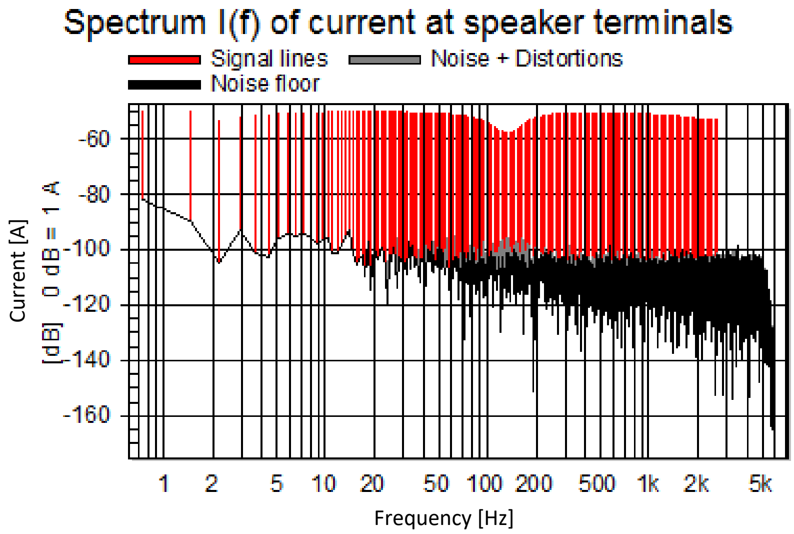


Figure 8: Measured current spectrum using a multitone stimulus

4.2 Impedance of the lossy inductance

The magnetic field generated by the voice coil induces eddy currents in the pole tips which generate a significant heating mechanism at higher frequencies. The losses appear in the real part of the electrical impedance rising with frequency in addition to the DC resistance R_e.
Figure 9 shows the magnitude and phase of the electrical impedance $Z_L(f)$ of the "lossy inductance" which is the residual electrical impedance after removing the DC resistance R_e and the effect of the back EMF. The magnitude of $Z_L(f)$ rises with a slope less than 6dB per octave, as expected from an ideal inductance. The phase response is about 70 degree above 200 Hz, indicating the electrical losses due to the eddy currents. The phase response below 200 Hz is very noisy because the magnitude is very small.

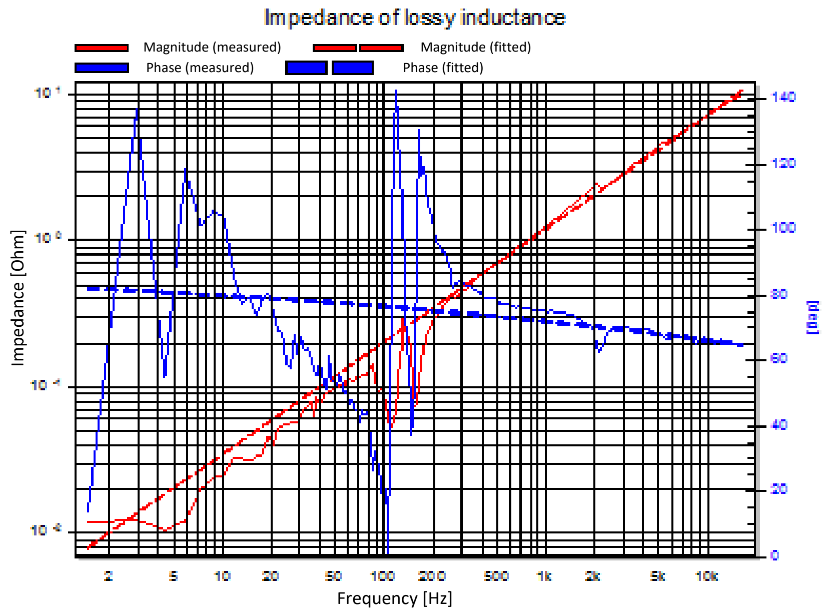


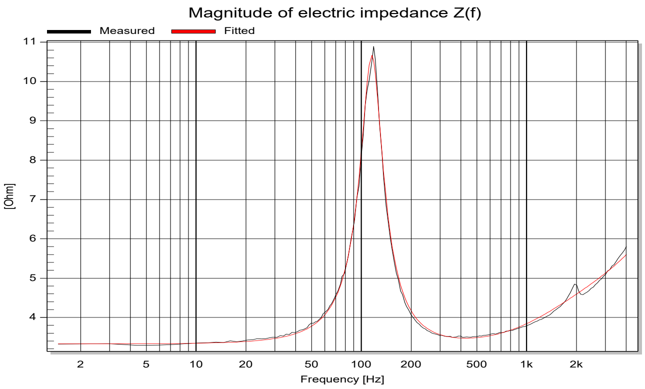
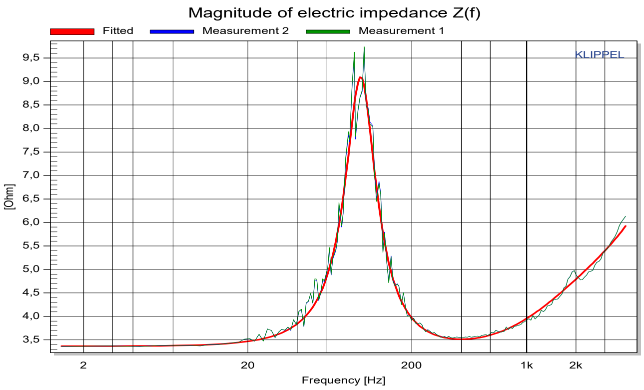
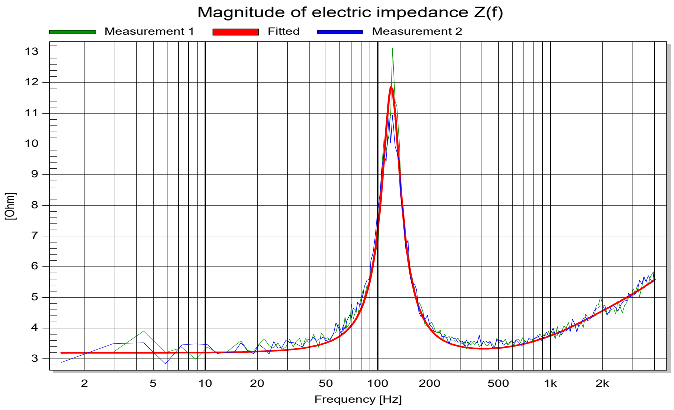
Figure 9: Magnitude and phase of the impedance $Z_L(f)$ representing the voice coil at higher frequencies

The impedance $Z_L(f)$ can only be very roughly approximated by an ideal inductance L_e. The LR2 model for electrical impedance uses in series a second ideal inductance L_2 and a resistance R_2 in parallel to L_2 which become active at higher frequencies. There are other models (Leach, Wright) using a mathematical model which cannot be represented as an electrical LR network.

4.2.1 Fitting of the electrical impedance

Finally the free parameters of the lumped parameter model are determined by minimizing the mean squared deviation between the measured and modeled impedance curve. The residual error is caused by measurement noise, nonlinear distortion and imperfections in the modeling. The amplitude of the stimulus should be adjusted carefully to ensure sufficient signal-to-noise ratio while avoiding generation of nonlinear distortion, as illustrated in Table 5.

Table 5: Assessing the results of the electrical impedance measurement

Good agreement between estimated and measured impedance curve  	**Criteria:** • Good signal to distortion ratio (> 30 dB) • Good signal to noise ratio (> 30 dB) • Low fitting error RMS (< 3 %)
Measured curve corrupted by nonlinear distortion  	**Criteria:** • Poor signal to distortion ratio (< 30 dB) • Good signal to noise ratio (> 30 dB) • Poor agreement between estimated and measured impedance curve • High fitting error RMS • Distortions are reproducible (identical results for different measurements with the same setup) **Remedy:** • Reduce amplitude of the stimulus
Measured curve corrupted by measurement noise  	**Criteria:** • Poor signal-to-noise ratio (< 30 dB) • Poor agreement between estimated and measured impedance curve • High fitting error RMS • Distortions are not reproducible (different results for different measurements with the same setup) **Remedy:** • Increase amplitude of the stimulus • Increase number of averaging • Use current sensor with higher sensitivity

4.3 Mechanical Parameter Measurement

The mechanical parameters such as force factor *Bl* cannot be identified by measuring the electrical input impedance of the driver. However, they can be calculated from the change of the electrical parameters caused by a known perturbation of the mechanical parameters according to Figure 10.

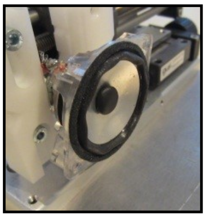
	1st Measurement of the electrical input impedance of the speaker operated in free air *without* added mass.		2nd Measurement of the electrical input impedance of the speaker operated in free air *with* added mass.

Figure 10: Measurement of the mechanical parameters by additional mass method

4.3.1 Additional Mass Method

Measuring the electrical impedance of the transducer with and without additional mass M_{add} attached to the diaphragm (Figure 10) reveals a shift in the resonance frequency, as shown in Figure 11.

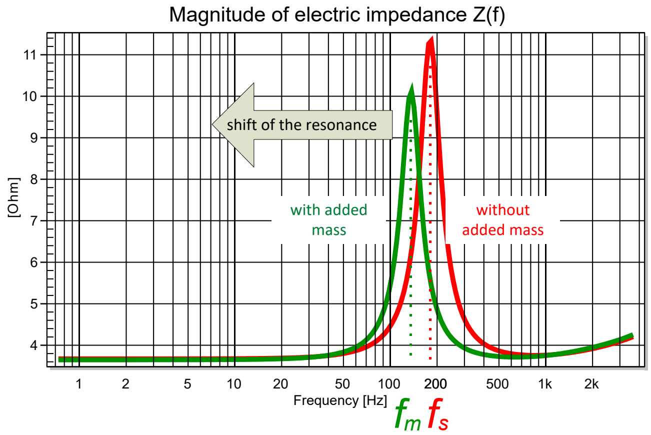


Figure 11: Input Impedance measurements of the Additional Mass Method

The added mass M_{add} should be 50% to 100% of the measured moving mass M_{ms} to achieve a distinct shift of the resonance and sufficient accuracy in the calculation of the mechanical parameters in Table 6.

Table 6: Calculation of the mechanical parameters using the Additional Mass Method

Step 1: Calculation of the moving mass using quality factor Q_{em} representing the electrical damping and resonance frequency f_m of the transducer with added mass and the corresponding parameters Q_{es} and f_s of the transducer without perturbation:	$M_{ms} = \frac{M_{add}}{\frac{Q_{em} f_s}{Q_{es} f_m} - 1}$
Step 2: Compliance of the suspension:	$C_{ms} = \frac{1}{(2\pi f_s)^2 M_{ms}}$
Step 3: Stiffness is the inverse of compliance C_{ms}:	$K_{ms} = \frac{1}{C_{ms}}$
Step 4: Force factor describes the coupling between the mechanical and electrical side of a transducer:	$Bl = \sqrt{\frac{2\pi f_s R_e M_{ms}}{Q_{es}}}$
Step 5: Mechanical resistance of total driver losses:	$R_{ms} = \frac{2\pi f_s M_{ms}}{Q_{ms}}$

4.3.2 Laser Measurement Technique

The add-mass method cannot be applied to small transducers and is time-consuming because it requires two measurements. The mechanical parameters can be measured by a single measurement using an additional mechanical sensor, such as a triangulation laser shown in Figure 12.

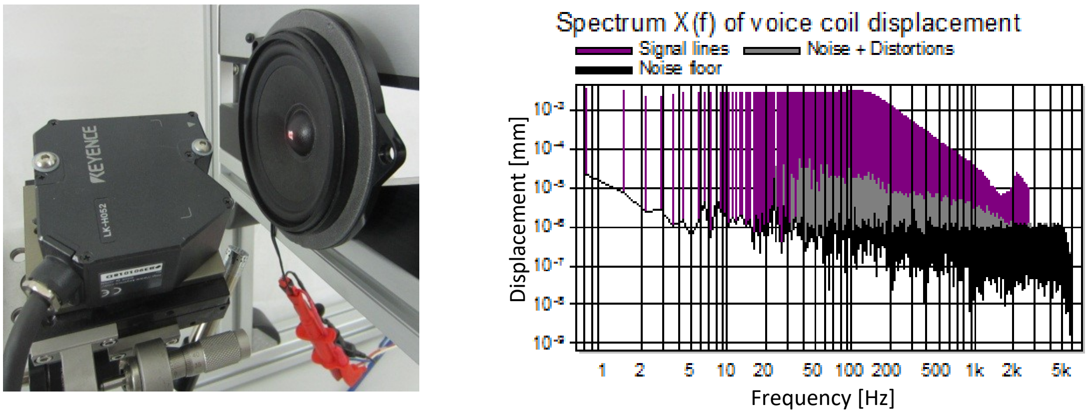


Figure 12: Triangulation laser (left) and spectrum (right) of the measured displacement signal

The laser measurement can be applied to any transducer when the cone is accessible to the optical sensor. The spectrum of the displacement using a multi-tone complex reveals the nonlinear distortion (grey lines in Figure 12) separated from the noise floor.

The transfer function between voltage and displacement

$$\underline{H}_x(f) = \frac{\underline{X}(f)}{\underline{U}(f)} = \frac{Bl}{\left(R_e + \underline{Z}_L(f)\right)\left(K_{ms} + j2\pi f R_{ms} - (2\pi f)^2 M_{ms}\right) + j2\pi f (Bl)^2}$$

calculated by the lumped parameters is fitted to the measured transfer function using output of the voltage and displacement sensor.

The lumped parameter model used in this hands-on training assumes that the suspension can be described by a constant stiffness K_{ms} giving a constant value of the magnitude $|H(f)|$ at low frequencies. However, the visco-elastic behavior of real suspension generates the so-called "creep effect." which causes a decrease of the stiffness $K_{ms}(f)$ and an increase of the resistance $R_{ms}(f)$ to lower frequencies. (This effect is also visible in Figure 13 but will be discussed in detail in a separate hands-on training dedicated to micro-speakers.)

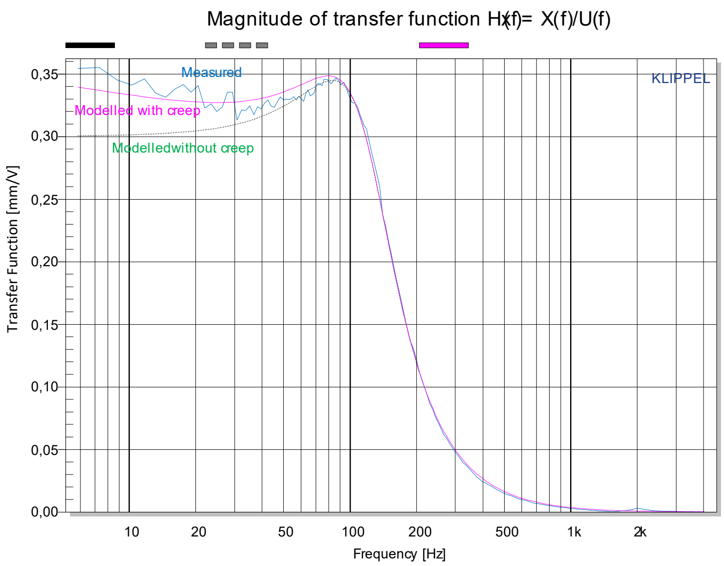


Figure 13: Magnitude of the transfer function $H_x(f)$ measured by using a laser sensor and predicted by lumped parameter modeling (with and without considering visco-elastic creep effect)

5. 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: Which parts of a cone loudspeaker affect the lumped parameters R_e?

- □ **MC a:** Voice coil
- □ **MC b:** Terminals, litz wire
- □ **MC c:** Cone, dust cap, voice-coil former
- □ **MC d:** Magnet, pole plate, back plate, pole piece
- □ **MC e:** Surround, spider

QUESTION 2: Which parts of a cone loudspeaker affect the lumped parameter *Bl*?

- □ **MC a:** Voice coil
- □ **MC b:** Terminals, litz wire
- □ **MC c:** Cone, dust cap, voice-coil former
- □ **MC d:** Magnet, pole plate, back plate, pole piece
- □ **MC e:** Surround, spider

QUESTION 3: Which parts of a cone loudspeaker affect the lumped parameter M_{ms}?

- □ **MC a:** Voice coil
- □ **MC b:** Cone, dust cap, voice-coil former
- □ **MC c:** Magnet, pole plate, back plate, pole piece
- □ **MC d:** Surround, spider

QUESTION 4: Which parts of a cone loudspeaker affect the lumped parameter C_{ms}?

- □ **MC a:** Voice coil
- □ **MC b:** Cone, dust cap, voice-coil former
- □ **MC c:** Magnet, pole plate, back plate, pole piece
- □ **MC d:** Surround, spider

QUESTION 5: Which mechanical parameters are related with C_{mes} representing moving mass in the electrical domain?

- □ **MC a:** Force factor *Bl*
- □ **MC b:** Compliance C_{ms} or stiffness K_{ms}
- □ **MC c:** Moving mass M_{ms}
- □ **MC d:** Mechanical resistance R_{ms}

QUESTION 6: Which parts of a loudspeaker affect the capacity C_{mes}?

- □ **MC a:** Voice coil
- □ **MC b:** Terminals
- □ **MC c:** Cone, dust cap, voice-coil former
- □ **MC d:** Magnet, pole plate, back plate, pole piece
- □ **MC e:** Surround, spider

QUESTION 7: Which mechanical parameters are related with L_{ces} representing compliance in the electrical domain?

- □ **MC a:** Force factor *Bl*
- □ **MC b:** Compliance C_{ms} or stiffness K_{ms}
- □ **MC c:** Moving mass M_{ms}
- □ **MC d:** Mechanical resistance R_{ms}

QUESTION 8: Which parts of a loudspeaker affect the inductance L_{ces} representing mechanical compliance in the electrical domain?

- □ **MC a:** Voice coil
- □ **MC b:** Terminals, litz wire
- □ **MC c:** Cone, dust cap, voice-coil former
- □ **MC d:** Magnet, pole plate, back plate, pole piece
- □ **MC e:** Surround, spider

QUESTION 9: Which parts of a loudspeaker affect the impedance $Z_L(f)$ representing lossy voice coil inductance at higher frequencies?

- □ **MC a:** Voice coil, voice coil former
- □ **MC b:** Terminals, litz wire
- □ **MC c:** Cone, dust cap
- □ **MC d:** Magnet, pole plate, back plate, pole piece
- □ **MC e:** Surround, spider

QUESTION 10: Which parts of a cone loudspeaker affect the resonance frequency f_s?

- □ **MC a:** Voice coil
- □ **MC b:** Terminals, litz wire
- □ **MC c:** Cone, dust cap, voice-coil former
- □ **MC d:** Magnet, pole plate, back plate, pole piece
- □ **MC e:** Surround, spider

QUESTION 11: Which parts of a cone loudspeaker affect the quality factor Q_{ms} representing mechanical damping only?

- □ **MC a:** Voice coil
- □ **MC b:** Terminals, litz wire
- □ **MC c:** Cone, dust cap, voice-coil former
- □ **MC d:** Magnet, pole plate, back plate, pole piece
- □ **MC e:** Surround, spider

QUESTION 12: Which parts of a cone loudspeaker affect the total quality factor Q_{ts}?

- □ **MC a:** Voice coil
- □ **MC b:** Terminals, litz wire
- □ **MC c:** Cone, dust cap, voice-coil former
- □ **MC d:** Magnet, pole plate, back plate, pole piece
- □ **MC e:** Surround, spider

6. Interpretation of linear parameter measurements (no hardware required)

Step 1: View the demo movie *Linear Lumped Parameter Measurement* provided at www.klippel.de/training to see how a practical measurement of the linear lumped parameters is performed.

Step 2: Install the KLIPPEL R&D software *dB-Lab* on your computer and download the database corresponding to this training.

Step 3: Start *db-Lab* by clicking on the file ***Training 1 Linear Lumped Parameter Measurement.kdbx***.

Step 4: In *dB-Lab* open the test object ***'1 Woofer 4inch in free air***, which contains a list of LPM measurements applied to a small woofer clamped in a laser measurement stand in free air.

Step 5: Click on the first operation ***1a LPM 0.005V*** and under the menu bar click on **"*Properties*"** to see the settings (voltage, frequencies, averaging) used in the measurement.

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

6.1 Finding the optimal voltage of the stimulus

QUESTION 13: Why should the measurement of the linear lumped parameters be performed at low amplitudes?

- □ **MC a:** To protect the transducer from overload and avoid a permanent damage of the speaker.
- □ **MC b:** The linear modeling of the transducer is only valid at low voice coil displacement where the effect of the loudspeaker nonlinearities can be neglected.
- □ **MC c:** To protect the ears of the operator.

QUESTION 14: What will ensure that the transducer (connected to a normal power amplifier with low output impedance) is operated in the linear domain?

- □ **MC a:** The voltage of the stimulus should be smaller than the maximal permissible voltage of the transducer defined by manufacturer.
- □ **MC b:** The nonlinear distortion generated in the input current signal at the resonance frequency should be 30 dB lower than the fundamental component.
- □ **MC c:** The nonlinear distortion generated in the terminal voltage at the resonance frequency should be 30 dB lower than the fundamental component.
- □ **MC d:** The generated voice coil peak displacement generated by the stimulus should be smaller than maximal (linear) peak displacement X_{max} defined by the manufacturer.
- □ **MC e:** The terminal voltage supplied to any transducer under test should be smaller than 1Volt rms.
- □ **MC f:** The peak displacement generated by the stimulus in any transducer under test should be smaller than 1 mm.

QUESTION 15: How is nonlinear distortion distinguished from the measurement noise by using a multi-tone stimulus?

- □ **MC a:** The difference between the signal component (Noise + Distortion), the fundamental component and the noise floor measured without stimulus shows the nonlinear distortion.
- □ **MC b:** The waveform of the measured signal reveals the nonlinear distortion.
- □ **MC c:** The fitting error of the electrical impedance (rms Z_e *(f)*) shows the nonlinear distortion

Step 6: Check the results of the operations ***1a, 1b*** and ***1c*** using different voltage settings 0.005 V, 0.8 V, and 0.1 V, respectively. Assess the level of the nonlinear distortion and the noise by comparing the fundamental lines with the lines *Noise + Distortion* and the *Noise Floor* in the result window ***"Current (f) Spectrum"***.

QUESTION 16: Which voltage value is the best for measuring the linear small signal parameters of the woofer shown in the database?

- □ **MC a:** High voltage U= 0.8 V, providing the best signal-to-noise ratio (SNR).
- □ **MC b:** Medium voltage 0.1 V, generating small values of nonlinear distortion while having an acceptable SNR.
- □ **MC c:** Low voltage U=0.005 V, to keep the nonlinear distortion as small as possible.

Step 7: Open the result windows "***Table Linear Parameters***" and "***Table Signal Characteristics***" and compare the resonance frequency f_s with the peak-to-peak displacement X_{pp} over the three measurements

QUESTION 17: Does the measured resonance frequency f_s depend on peak-to-peak displacement X_{pp}?

- □ **MC a:** Yes, the resonance frequency decreases with increasing peak to peak displacement due to the temporal softening of the suspension (visco-elastic effect similar to the creep phenomenon) in the small signal domain.
- □ **MC b:** No, the resonance frequency is constant and independent of the peak displacement.

6.2 Finding the optimal spectral properties of the multi-tone stimulus

Step 8: Check the results of the operations ***2a, 2b, 2c*** and ***2d*** where the spectral properties of the stimulus are varied and investigate the effect on the fitting errors *rmse Z* and *rmse Hx* in the result window ***"Table Linear Parameter"***.

QUESTION 18: How is the upper frequency limit F_{max} adjusted in a multi-tone complex?

- □ **MC a:** F_{max} should be set to 18 kHz if the parameters describing the lossy inductance (e.g. $Z_L(f)$) should be identified over the full audio band.
- □ **MC b:** F_{max} should be set to 500 Hz for any kind of transducer.
- □ **MC c:** F_{max} should be set to $20f_s$ if the accuracy of the mechanical parameters is more important than the identification of the inductance over the full audio band.
- □ **MC d:** The setting of F_{max} is not critical and will not affect the measurement of the lumped parameters as long as the resonance frequency $f_s < F_{max}$.

QUESTION 19: How is the relative resolution (number of excited lines per octave) adjusted in a multi-tone complex?

- □ **MC a:** At least 1 line should be within 1 octave to provide sufficient excitation by the multi-tone signal.
- □ **MC b:** 16 lines per octave provide sufficient resolution to describe the resonance peak in the electrical impedance, while keeping the maximal displacement of the voice coil displacement as small as possible (avoiding nonlinear distortion).
- □ **MC c:** The density of the exciting components in the multi-tone complex should be as high as possible (at least 40 lines per octave) to measure the impedance curve at maximal resolution.

QUESTION 20: How is sufficient accuracy ensured in the measurement of the dc resistance R_e?

- □ **MC a:** Setting F_{max} as high as possible to measure the impedance accurately at high frequencies.
- □ **MC b:** Sensitive sensor used in the hardware for measuring the electric current signal flowing in the transducer.
- □ **MC c:** Sufficient number of averaging to improve the signal-to-noise ratio (SNR) in monitored voltage and current signal.
- □ **MC d:** Optimal setting of the voltage to ensure sufficient signal-to-noise ratio and low distortion.
- □ **MC e:** Sufficient resolution (at least 16 lines per octave) to ensure that the lowest lines of the current spectrum are below 1 Hz (close to the DC).

QUESTION 21: Which measurement has been performed with a proper stimulus to measure the mechanical parameters of the woofer operated in the target application below 4 kHz.

- □ **MC a:** Operation 2a LPM 500 uses a stimulus which is low-pass filtered below 500 Hz.
- □ **MC b:** Operation 2b LPM 2.6k uses a stimulus which is low-pass filtered below 2.6 kHz to consider the influence of the inductance.
- □ **MC c:** Operation 2c LPM 16k uses a stimulus which is ideal to identify the lossy inductance at high frequencies.
- □ **MC d:** Operation 2d LPM 2.6k res 1/3 oct uses a stimulus which is low-pass filtered below 2.6 kHz and provides a spectral resolution which is sufficient to identify the mechanical resonance.

6.3 Finding the optimal inductance model

Step 9: Select operation ***2c LPM 16k*** and view the results windows "***Impedance Magnitude", "Lossy Inductance"*** and ***"Table Linear Parameters".*** Open the property page "***Im/Export"*** and investigate the effect of the Inductance Models (*LR2, Wright, Leach*). Assess the quality of the fitting by the characteristic *rmse Z* in the "***Table Linear Parameters".***

QUESTION 22: Which inductance model gives the best fitting in operation *2c LPM 16k*?

- □ **MC a:** LR2
- □ **MC b:** Leach
- □ **MC c:** Wright

QUESTION 23: Why is the selection of an optimal inductance model important?

- □ **MC a:** In order to measure dc resistance R_e precisely
- □ **MC b:** In order to measure the resonance frequency f_s precisely
- □ **MC c:** To measure the quality factors Q_{ms} and Q_{es} precisely, which is important for an accurate measurement of the mechanical parameters (Bl, K_{ms}, M_{ms}, R_{ms}) using the perturbation or laser method.

6.4 Finding the optimal number of averaging

QUESTION 24: How many dB can the signal to noise ratio be improved by averaging the measured signals N=16 times.

- □ **MC a:** 12 dB
- □ **MC b:** 24 dB
- □ **MC c:** 6 dB

Step 10: Compare the operations ***3a, 3b, 3c*** and ***3d*** and consider the effect of the averaging.

QUESTION 25: Does the measured improvement of the SNR agree with the theoretical value above 300 Hz by applying 16 times averaging?

- □ **MC a:** Yes, the SNR in the current signal is improved by approximately 6 dB above 300 Hz.
- □ **MC b:** Yes, the SNR in the current signal is improved by approximately 12 dB above 300 Hz.
- □ **MC c:** Yes, the SNR in the current signal is improved by approximately 24 dB above 300 Hz.
- □ **MC d:** No, there are other disturbances which are correlated with the stimulus which cannot be suppressed by averaging.

QUESTION 26: Does the averaging reduce the level of the nonlinear distortions generated by the transducer?

- □ **MC a:** Yes, the nonlinear distortion generated at frequencies below or above resonance f_s are reduced by averaging.
- □ **MC b:** No, the nonlinear distortions generated by the transducer are deterministic and reproducible and will not be reduced by averaging.

6.5 Additional Mass Method

Step 11: Check the results of the operations ***4 LPM added mass*** where the laser was disconnected and the determination of the mechanical parameter was done with the perturbation method additional mass.

QUESTION 27: Is this measurement performed with a useful setup?

- □ **MC a:** No, the added mass M_{add} is too small.
- □ **MC b:** Yes, a useful value of the added mass M_{add} is used.
- □ **MC c:** Yes, the distortion in the input current is more than 30dB below the fundamental components.

QUESTION 28: What are possible reasons for the differences between the lumped parameters determined by the laser measurement and the added mass method?

- □ **MC a:** Inaccurate measurement of the added mass before attaching it to the cone.
- □ **MC b:** Inaccurate laser calibration.
- □ **MC c:** Significant change of ambient temperature and humidity between the two measurements (caused by a break between the two measurements).
- □ **MC d:** The transducer operated with and without additional mass generates different peak displacement for the same stimulus.
- □ **MC e:** Mass is not firmly attached to the cone.
- □ **MC f:** Change of the static (atmospheric) sound pressure between the two measurements.

QUESTION 29: What are advantages and disadvantages between these two measurement methods?

- □ **MC a:** The laser method is faster than the added mass method because it can be accomplished in one step.
- □ **MC b:** The laser method can be applied to small transducers as long as the cone's surface is accessible for an optical measurement.
- □ **MC c:** The laser method determines the lumped parameters from the measured displacement, but requires no access to the electrical terminals to measure voltage and current.

6.6 Potential User Errors

Step 12: The operations ***5a, 5b*** and ***5c*** are invalid due to typical user errors. Compare those measurement with the optimal measurement discussed before.

Step 13: Inspect operation ***5a*** where the mechanical mass M_{ms} is much higher than in the previous measurements ***4 LPM added mass*** applied to the same transducer.

QUESTION 30: Which of the following statements is true?

- □ **MC a:** An additional mass was added to the transducer which reducing the resonance frequency f_s.
- □ **MC b:** A wrong calibration factor for the laser sensor hardware is used (*Table Signal Characteristics*) causing a significant shift of the magnitude of transfer function $H_x(f)$. This affects all mechanical parameters while the electrical parameters are precise.
- □ **MC c:** There is a loose contact of the speaker cable at the transducer terminal causing an increase of the dc resistance R_e. This affects all lumped parameters identified.
- □ **MC d:** An inductance model is used which provides poor fitting at higher frequencies.

Step 14: Inspect operation ***5b*** where the mechanical mass M_{ms} is much lower than in the previous measurements ***4 LPM added mass*** applied to the same transducer.

QUESTION 31: What is the cause for that?

- □ **MC a:** The laser sensor provides no displacement signal (fundamental components are identical with the noise floor).
- □ **MC b:** An optical problem (obstacle) causes significant distortion (steps) in the output signal of the laser sensor as shown waveform in the result window *x(t*).
- □ **MC c:** No white dot is applied on the target surface to provide sufficient light for the laser sensor.
- □ **MC d:** The laser sensor was not directed in a perpendicular direction to the target surface (causing an attenuation of the laser output signal and a minor error in the *Bl* factor but no distortion in the laser signal).
- □ **MC e:** The transducer was not firmly clamped in a stand (causing additional resonances in the electrical impedance).

Step 15: Inspect operation ***5c*** where the dc resistance R_e is slightly higher than in the previous measurements ***4 LPM added mass*** applied to the same transducer.

QUESTION 32: What might be the reason(s) for that?

- □ **MC a:** The transducer was not firmly clamped in the speaker stand in vertical orientation causing an additional resonance peak in the impedance curve.
- □ **MC b:** There is a loose contact of the speaker cable at the transducer terminals causing short interrupts in the electrical signals. The interrupts appear as distortion in current signal and have the same spectral distribution as the fundamental components (minimum at f_s). In contrast the transducer produces nonlinear distortion which have maximum at f_s in the current spectrum.
- □ **MC c:** A suboptimal inductance model has been selected which cannot fit the electrical impedance at higher frequencies.
- □ **MC d:** The voltage of the stimulus is too high and the transducer nonlinearities produce significant distortion in the result window "*Current (f) Spectrum*" (the distortions are maximal at the resonance frequency f_s).

7. Performing Measurements (Hardware required)

If the KLIPPEL measurement system is available, performing a practical measurement of the transducer (woofer) with resonance frequency $f_s < 200$ Hz is recommended. However, this is optional and is focused on the practical skills in handling transducers and in learning more about measurement techniques.

7.1 Setup the Hardware (with Klippel Analyzer 3)

After watching the demo movie *Training 1 Linear Lumped Parameter Measurement*, connect the hardware components as shown in the video and Figure 14 by doing the following steps:

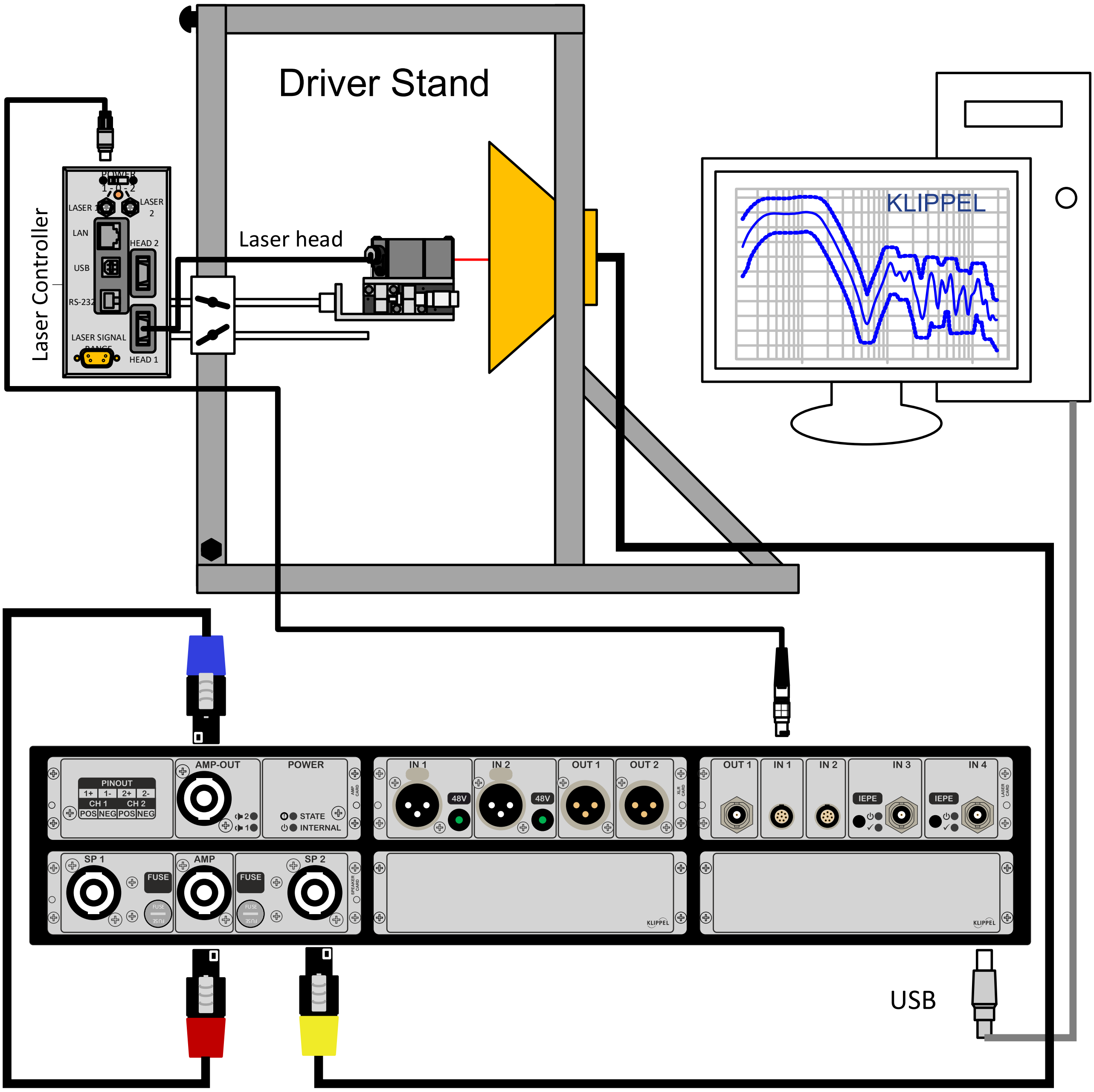


Figure 14: Hardware components required for Linear Parameter Measurement (LPM)

Step 16: Connect the power supply (delivered by KLIPPEL) with the ***POWER*** connector at the rear side of the *Klippel Analyzer 3 (KA3)*.

Step 17: Connect *KA3 Amplifier-Card* ***AMP-OUT*** to the *KA3Speaker-Card* ***AMP*** input.

Step 18: Alternatively, if no *KA3 Amplifier-Card* is available or an external amplifier should be used connect the *KA3 XLR-Card* ***OUT 1*** or *KA3 Laser-Card* ***OUT 1*** to the external amplifiers input and the external amplifiers output to the *KA3Speaker-Card* ***AMP*** input.

Step 19: Clamp the transducer firmly at the speaker stand (*Pro Driver Stand*) in vertical orientation. (It is recommended to clamp it at its magnet to avoid bending its frame.)

Step 20: Connect the *KA3 Speaker-Card* ***SP 2*** to the terminals of the transducer, using the Klippel speaker cable shipped with the system.

Step 21: Connect the KA3 via USB to a computer.

Step 22: Connect the *laser sensor head* with the *laser controller* and connect the *laser controller* output to the *KA3 Laser-Card* ***IN3*** input.

Step 23: Setting up the Laser Displacement Sensor the first time it needs to be calibrated as shown in the related video or according to *Hardware Manual / Sensor Handling / Laser Sensors / Calibration and Verification*.

Step 24: If a previous calibration just has to be verified follow the instruction at the *Hardware Manual / Sensor Handling / Laser Sensors / Calibration and Verification / Laser Accuracy Check*. Or verify the whole measurement system by performing a LPM measurement at a well-known laboratory reference speaker, which could be the Klippel delivered *Example Speaker*. See related *Example Speaker Manual*.

Step 25: Direct the laser beam to the centre of the dust cap in perpendicular direction. Take care that there are no obstacles near the laser beam.

Step 26: Apply a white dot on the target surface cone (TippEx® or a small white sticker).

Step 27: Bring the calibrated laser head to the center of the working range. The green LED (Keyence-Laser) should be on without flashing. For following measurements only the center position of the laser sensor has to be checked. The calibration remains constant and should be verified from time to time or from each independent user.

Step 28: Adjust the output signal routing at the *dB-Lab / Hardware / KA3 / Signal Configuration*:

Output = Amp-Card for shown setup with KA3 internal Amp-Card

Output = XLR-Card or (Laser-Card if no XLR-Card is available) for usage of external amplifier

7.2 Setup the Hardware (with discontinued Distortion Analyzer 2)

After watching the demo movie *Linear Lumped Parameter Measurement*, connect the hardware components as shown in 15 by doing the following steps:

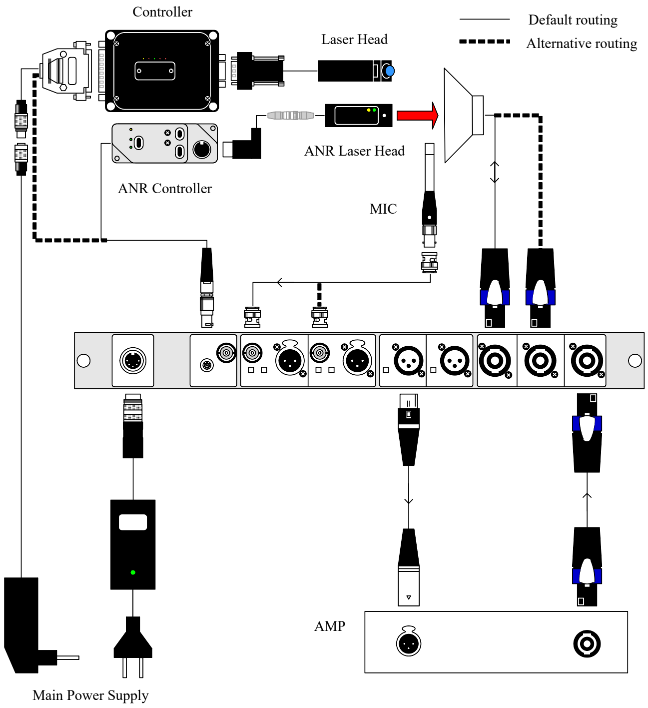


Figure 15: Hardware components required for Linear Parameter Measurement (LPM)

Step 29: Connect XLR output ***OUT1*** on the rear side of the *Distortion Analyzer (DA)* with the XLR input of the Amplifier.

Step 30: Connect the amplifier output to the *DA* Speakon Input ***AMPLIFIER***.

Step 31: Connect the *DA* Speakon output ***Speaker 2*** with the loudspeaker terminals by using the special speaker measurement cable.

Step 32: Connect the laser head 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: After switching the ***"POWER"*** on the *DA* press ***"ENTER"*** to activate the stand alone mode of the *DA*. Move with the cursor buttons ↓ and ↑ in the menu to **Displacement Meter** and press ***"ENTER"*** again.

Step 35: Check the calibration of the laser head by the following method depending on the laser type:

a. Keyence laser with micrometer screw:

Adjust the distance of the laser head from a firm target to ensure that the laser is operating in the middle of its working range (green LED stops flashing in the center position) and the display shows a displacement ***X*** which is close to zero. Use the cursor button → to select the distance measurement ***"D"*** and press the ***"ENTER"***. Select the menu item ***"ZERO"*** and press ***"ENTER"*** to activate the difference measurement referred to the current position. The value ***D*** should be closer to zero. Move the laser sensor 2 mm towards the target by turning the micrometer screw (1 turn = 0.5 mm) and view the difference ***D*** displayed. Note the difference should be positive and close to 2 mm.

b. ANR laser with reference stair*:*

Adjust the distance of the laser head from a firm target to ensure that the laser is operating in the middle of its working range (yellow LED stops flashing in the center position) and the display shows a displacement ***X*** which is close to zero. Use the cursor button → to select the distance measurement ***"D"*** and press the ***"ENTER"***. Select the menu item ***ZERO*** and press ***ENTER*** to activate the difference measurement referred to the current position. The value ***D*** should be closer to zero. Move the laser sensor 10 mm in vertical direction to the next step on the stair which reduces the distance between laser head and target by 10 mm. Check the measured difference ***D*** shown on the display.

If there is a significant difference (larger than 5%) then repeat the measurement to confirm the result. If the laser needs a new calibration follow the instructions given in the manual Hardware Guide/Laser Displacement Meter/Laser Calibration.

Step 36: Clamp firmly the transducer into the speaker stand vertically. Connect the speaker cable to the transducer.

Step 37: Direct the laser beam to the centre of the dust cap in perpendicular direction. Take care that there are no obstacles near the laser beam.

Step 38: Apply a white dot on the target surface cone (TippEx® or a small white sticker).

Step 39: Bring the laser head to the center of the working range. The yellow LED (ANR-Laser) or the green LED (Keyence-Laser) should be on without flashing.

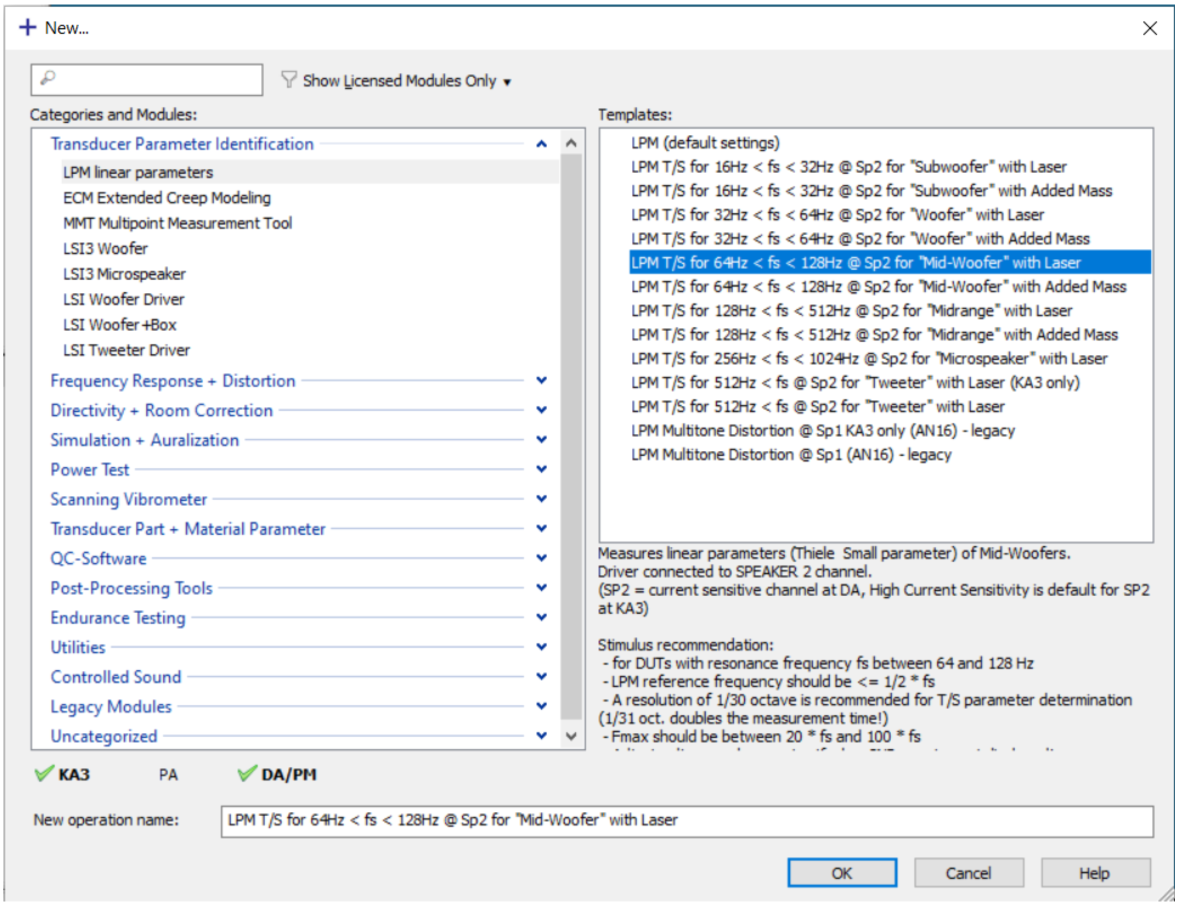
7.3 Measurement using the Laser sensor

Step 40: Start the measurement software *dB-Lab* of the R&D system.

Step 41: Create a new database: click on ***"Project"*** → ***"Select Database"*** then ***"New"***. Name the database and browse for a placing for saving. Press ***"OK"***.

Step 42: Create a new object with an appropriate name by selecting .

Step 43: Create a new operation by selecting  and selecting the measurement template according fs of the DUT. For Klippel Example Speaker most likely: "LPM T/S for 64Hz < fs < 128Hz @ Sp2 for "Mid-Woofer" with Laser" provided by *dB-Lab*.



If fs of the DUT is not known, starting with the mid-woofer template will allow to determine fs.

Step 44: Click with right mouse button on this operation and select ***"Properties"***.

Step 45: Enter the ***Diameter*** and ***nominal Impedance*** of the driver in the property page *Driver (For details look for "dB-Lab Manual chapter 4.8.3 Driver Property Page")*. Both values could also be filled in afterwards or kept empty if not known.

Step 46: Remain all other settings at the Property Page at its template values.

Step 47: Start the measurement by pressing the green arrow.

Step 48: Check the measurement results by viewing the signal to noise ratio in current, displacement and voltage and the fitting of the curves.

If measurement setup is not optimal click with the right mouse button on the operation and select ***"Duplicate"***. Open the property page of this operation and change the setting. Repeat the last measurement until having a satisfying result.

7.4 Measurement using the Added Mass Method

Step 49: Use template for added mass measurement. For each setup an added mass variant is available. If stimulus settings for laser measurement before have been adopted use the same adopted setting for added mass measurement as well.

Step 50: Click with right mouse button on the operation and select ***"Properties"***.

Step 51: Start the first measurement by pressing the green arrow.

Step 52: Attach the added mass to the diaphragm. Select the radio button ***with mass*** and specify the added mass on property page *Method*.

Step 53: Start the second measurement at the same operation by pressing the green arrow. (The Warning "Results will be deleted" from SW can be accepted.)

Step 54: Check the measurement results by viewing the signal to noise ratio in current, displacement and voltage and the fitting of the curves.

Step 55: If measurement setup is not optimal click with the right mouse button on the operation and select ***"Duplicate"***. Open the property page of this operation and change the setting. Repeat Step 51: to Step 55: to achieve a satisfying result.

7.5 Verification of the Measurement Results

Step 56: Compare the results of the laser method with the results of the added mass method. Find the lumped parameters which show significant deviations.

Step 57: Discuss the causes of the deviations.

Step 58: Check the hardware, the properties of the stimulus and other setup parameters.

Step 59: Repeat the measurement until you get a satisfying agreement between the two independent measurements.

8. Further Literature

User Manual for the KLIPPEL R&D SYSTEM – *Linear Parameter Measurement*

Specification S2 *Linear Parameter Measurement* (LPM):

http://www.klippel.de/fileadmin/klippel/Bilder/Our_Products/R-D_System/PDF/S2-LPM.pdf

Paper *Fast and accurate measurement of linear transducer parameters:*
http://www.klippel.de/uploads/media/Fast_and_Accurate_Linear_Parameter_Measurement_02.pdf

Application Note Maximizing LPM Accuracy:
http://www.klippel.de/fileadmin/klippel/Files/Know_How/Application_Notes/AN_25_Maximizing_LPM_Accuracy.pdf