Measuring the Nonlinear, Lossy, Frequency-dependent Voice Coil Inductance

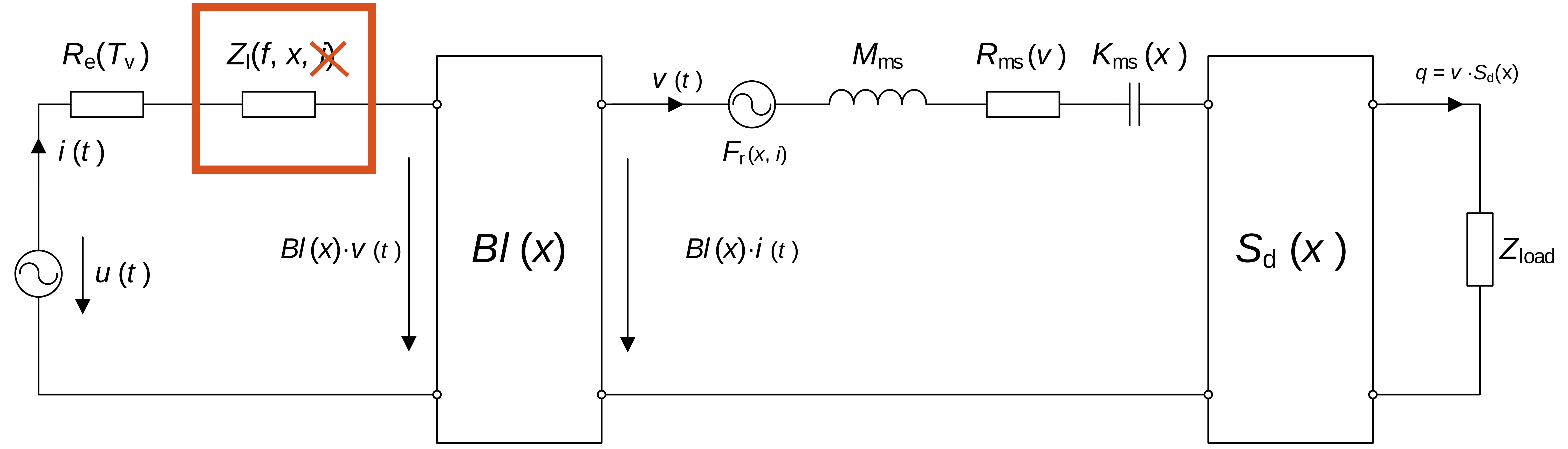
by Jonathan Gerbet, Wolfgang Klippel

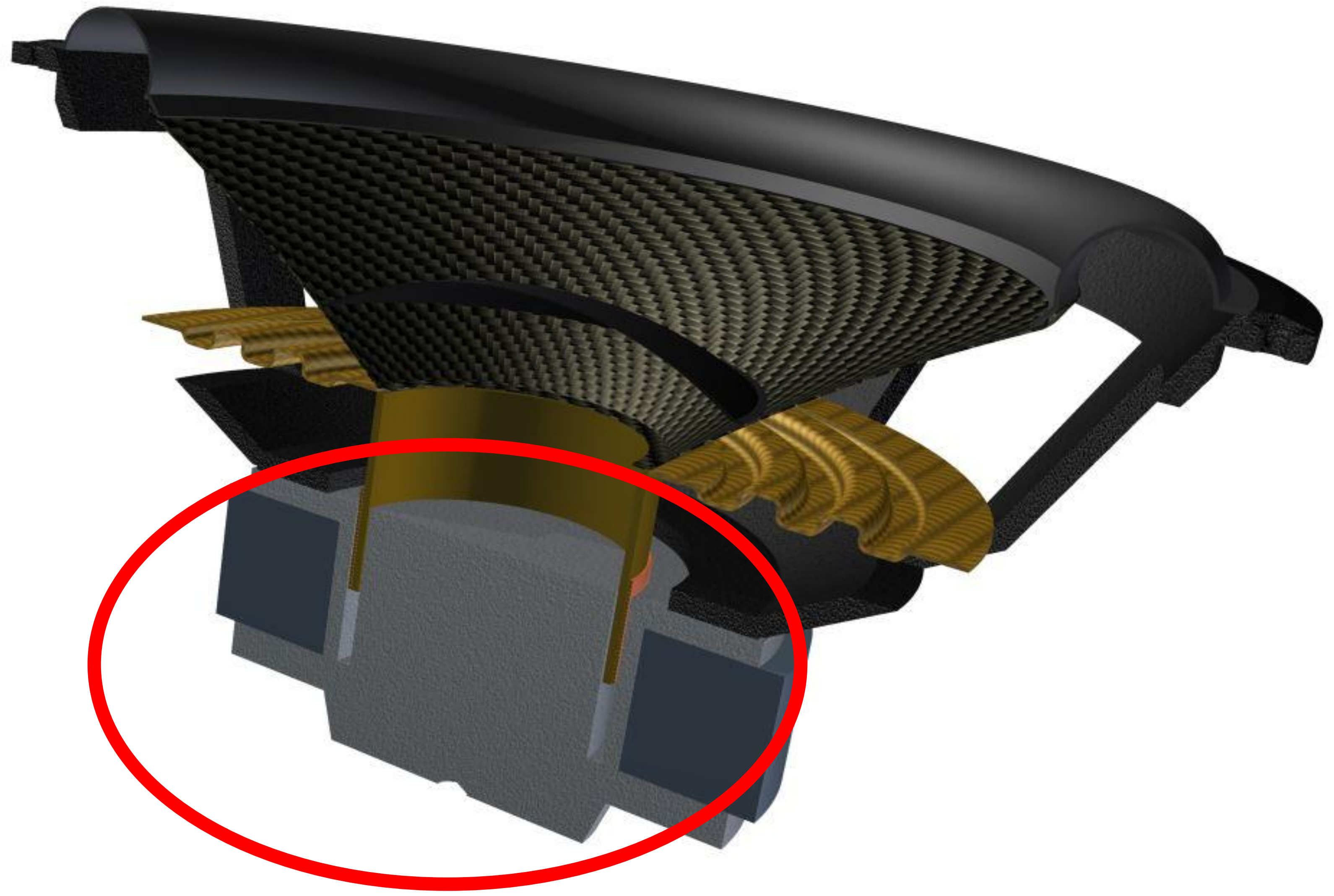
Overview

1. Motivation
2. Inductance Modeling
3. Inductance Measurement
4. Interpretation

Motivation

Measuring an accurate inductance model





- the voice coil is modeled with
  - a time-variant DC resistance
  - a dynamic nonlinear inductance which depends on frequency and voice coil displacement
  - current dependency and magnetic hysteresis is not considered in this presentation

GOALS:
- Robust, easy-to-use, and accurate measurement
- Easy interpretation of the results

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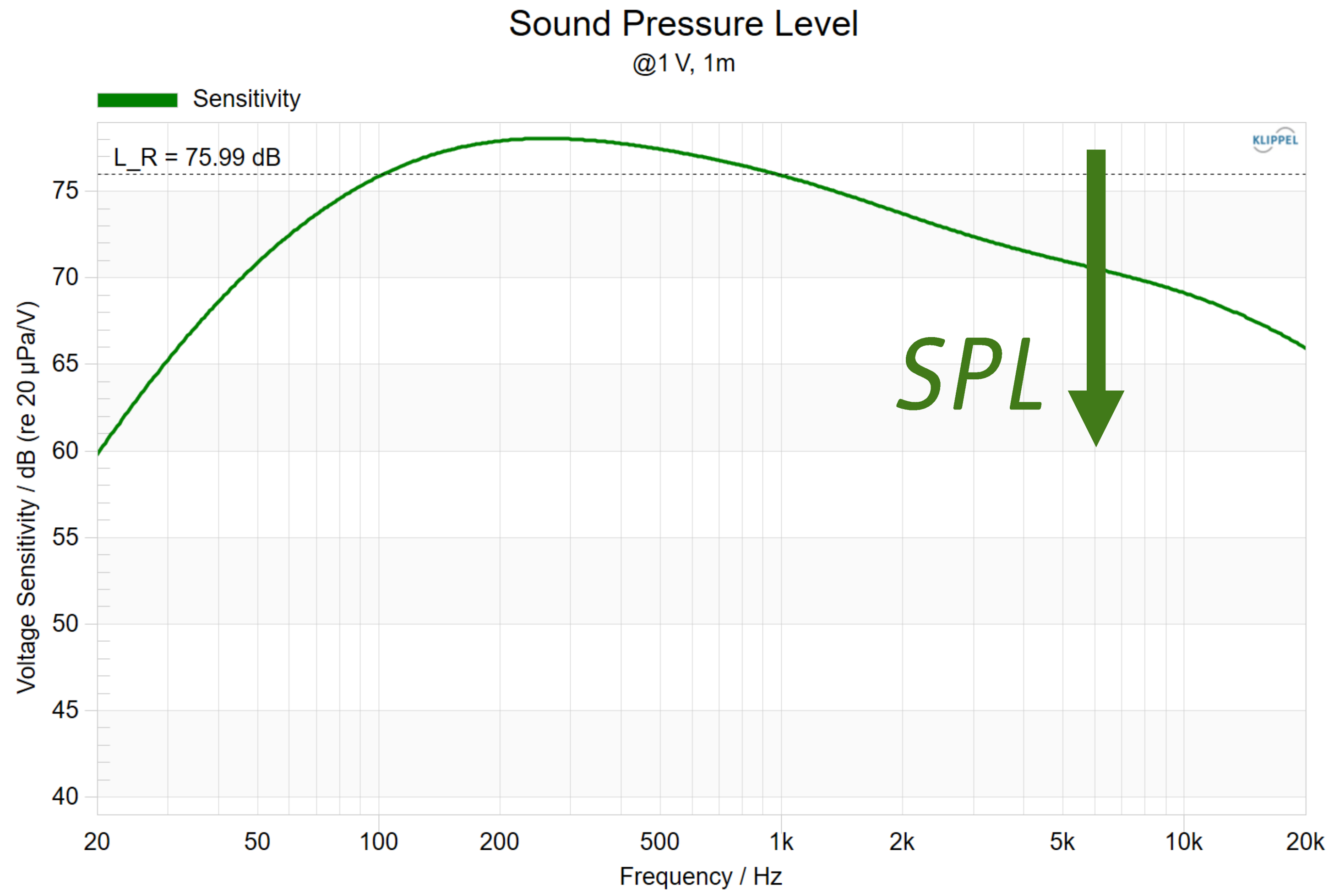
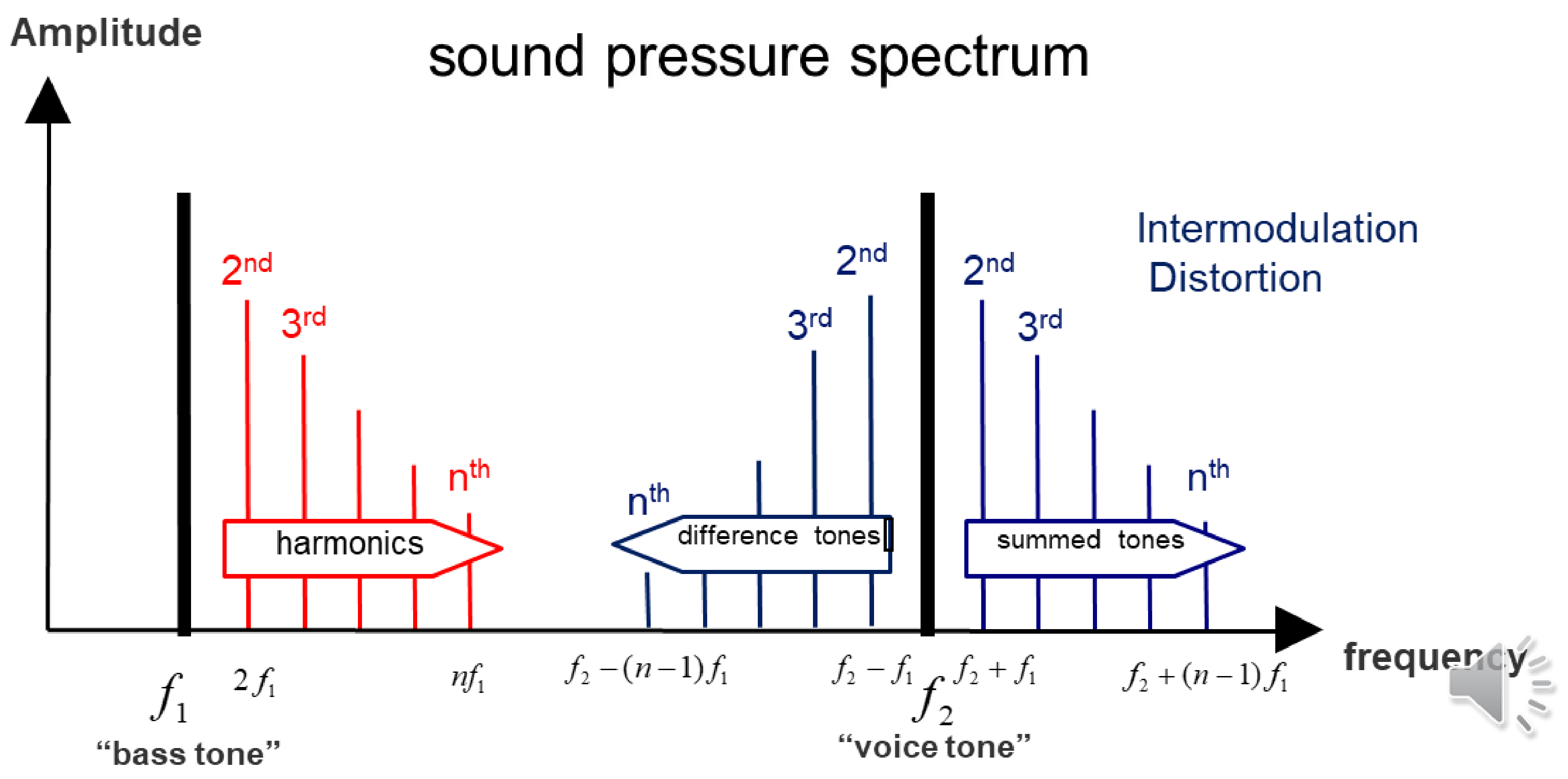
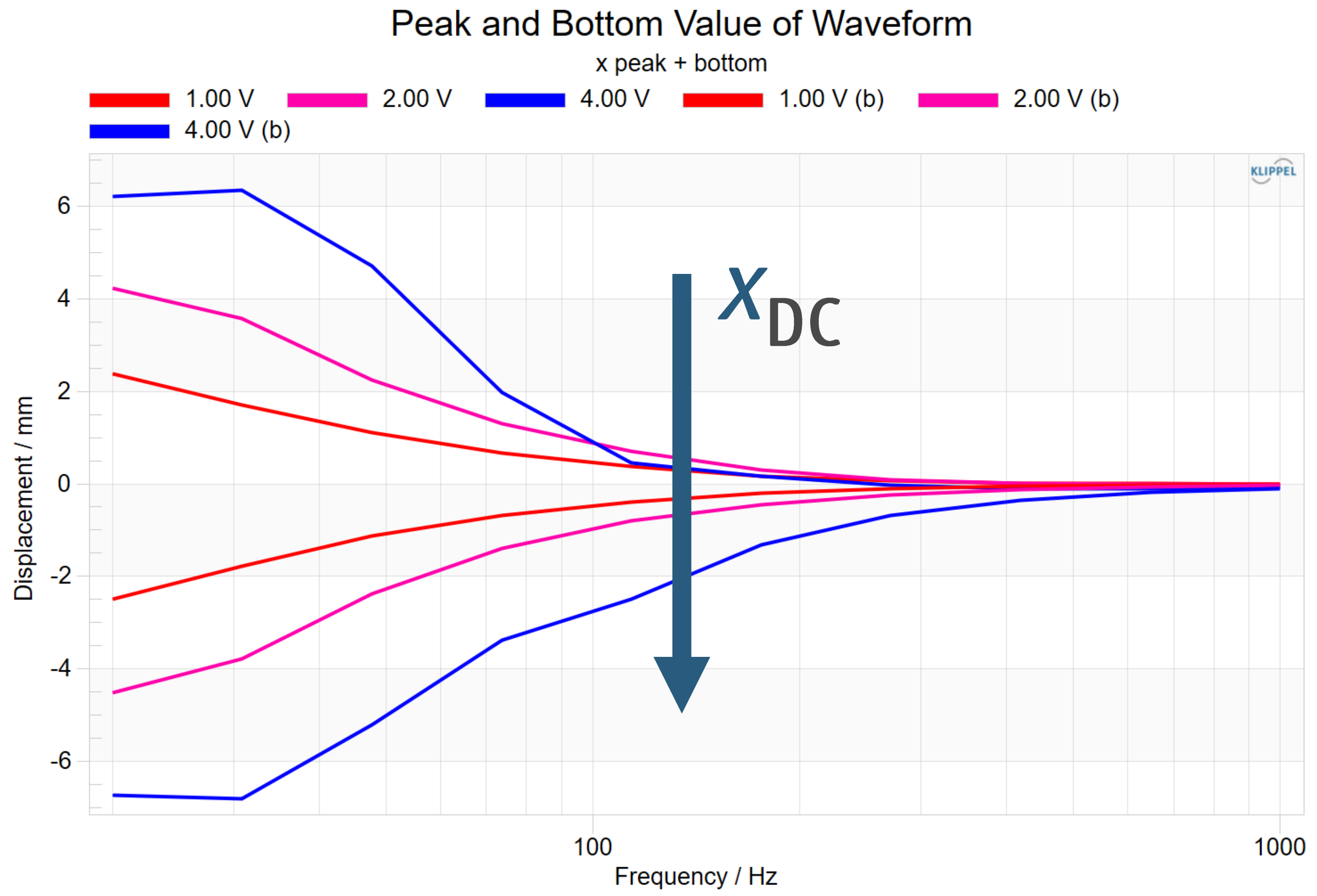
Motivation

Why measuring the nonlinear self-inductance?

- decreases the voltage sensitivity and efficiency
- creates nonlinear distortion (HD, IMD) that degrades the audio quality
- DC displacements decrease voice coil stability (reluctance force)







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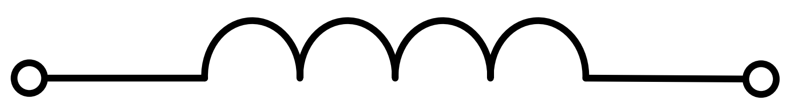
Inductance Modeling

Ideal Inductance

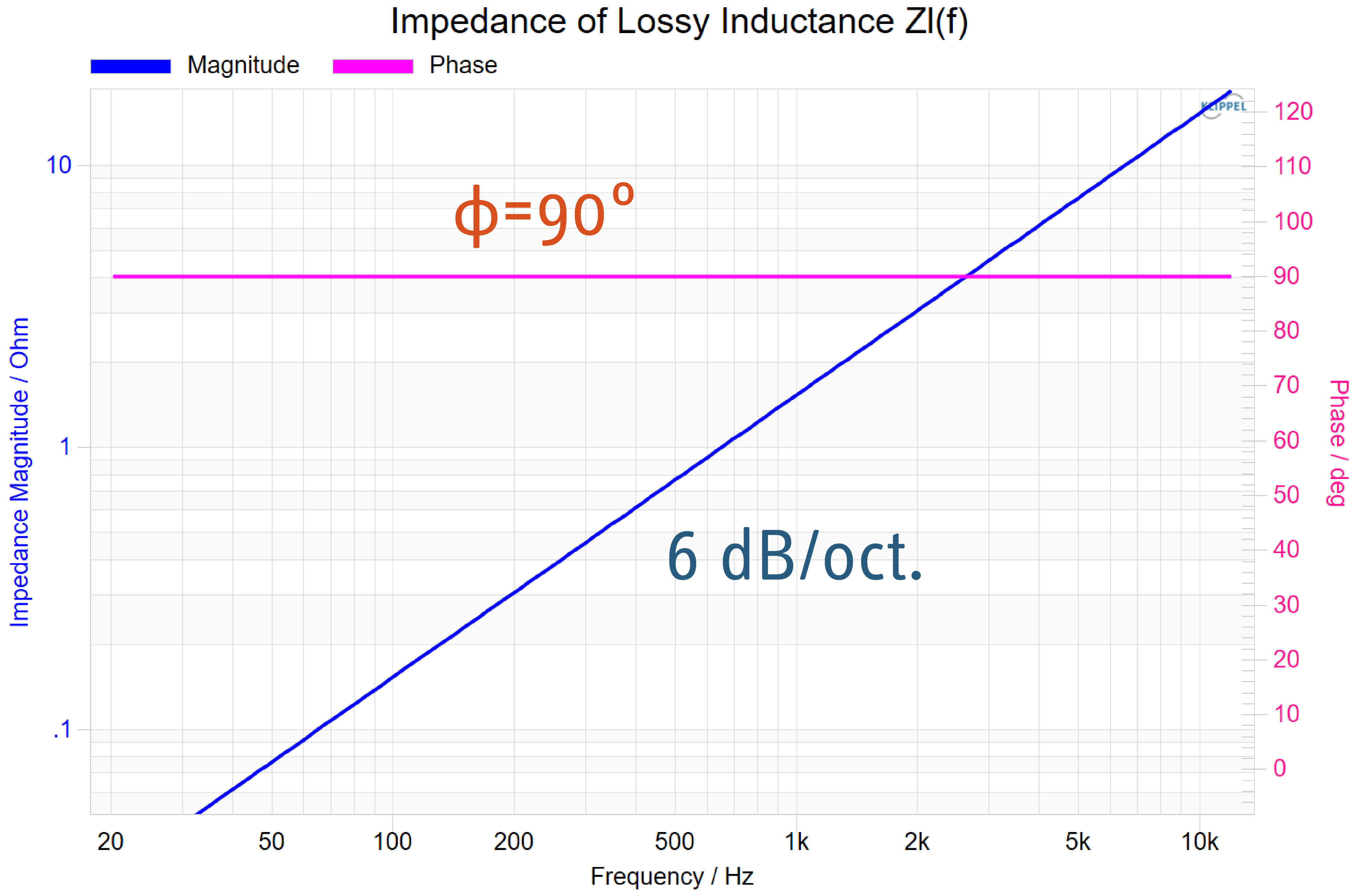
- Ideal inductance is purely reactive
  - Magnitude increases by 6dB/oct
  - Constant Phase of 90°
- Can be modeled with a single nonlinear inductance parameter L_e

L_e



$$Z_L(j\omega) = L_e j\omega$$

- Does not consider magnetic losses

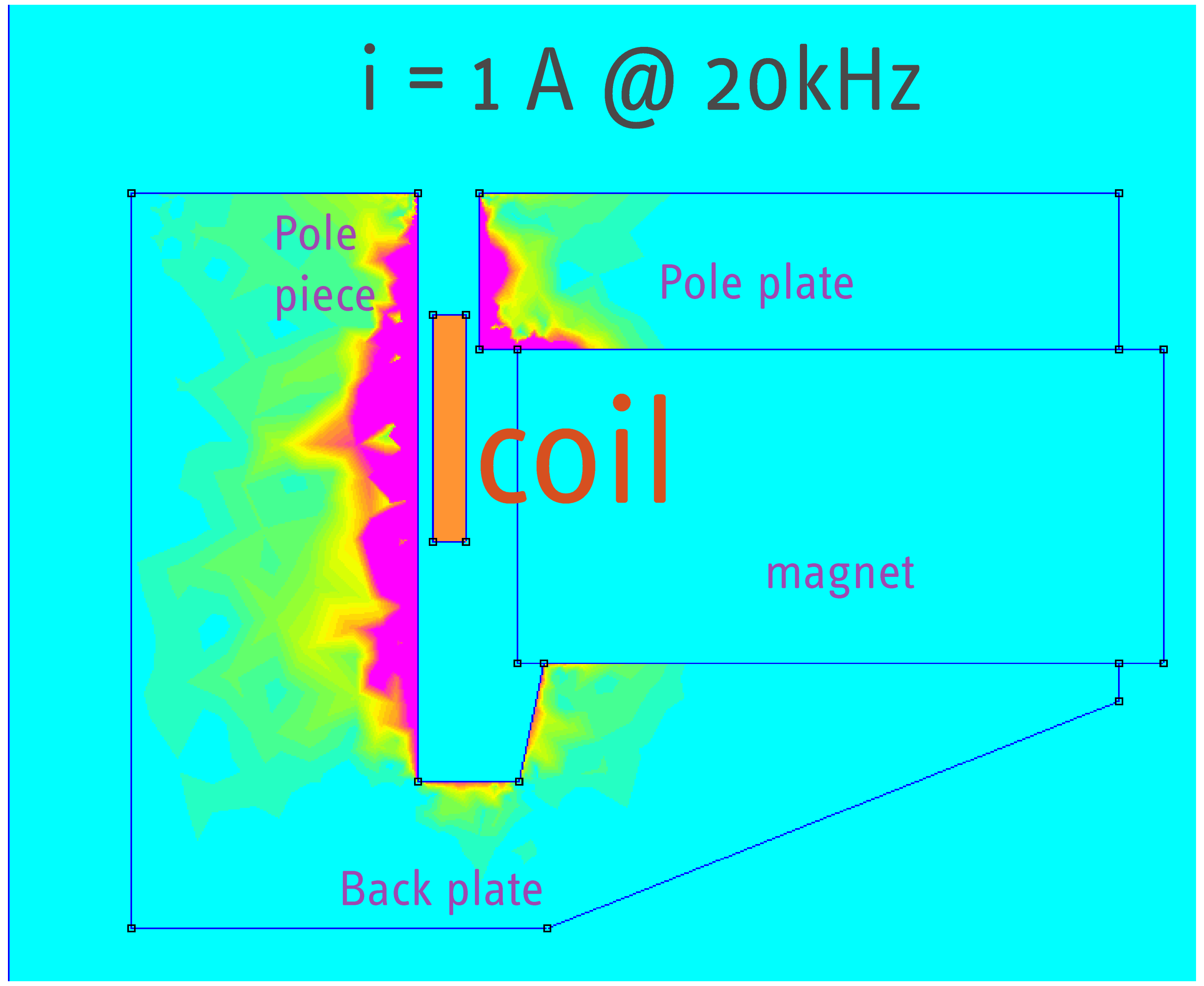


Inductance Modeling

Losses

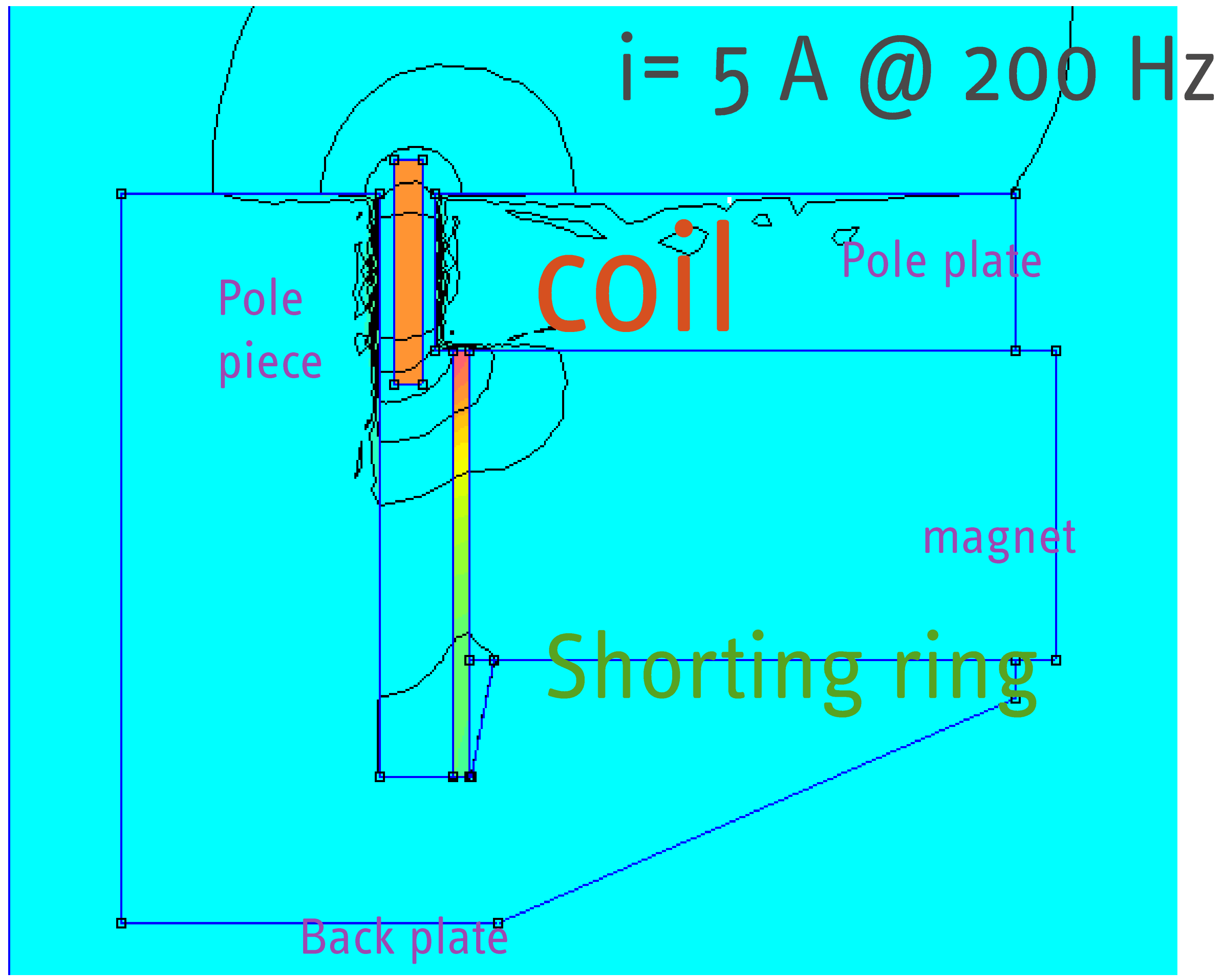
Eddy Currents

Current density J(r) in magnetic system <u>without shorting material:</u>



Shorting Material

Current density J(r) in the magnetic system <u>with shorting ring:</u>



➢ Energy is dissipated into heat. This cannot be explained by an ideal inductance!

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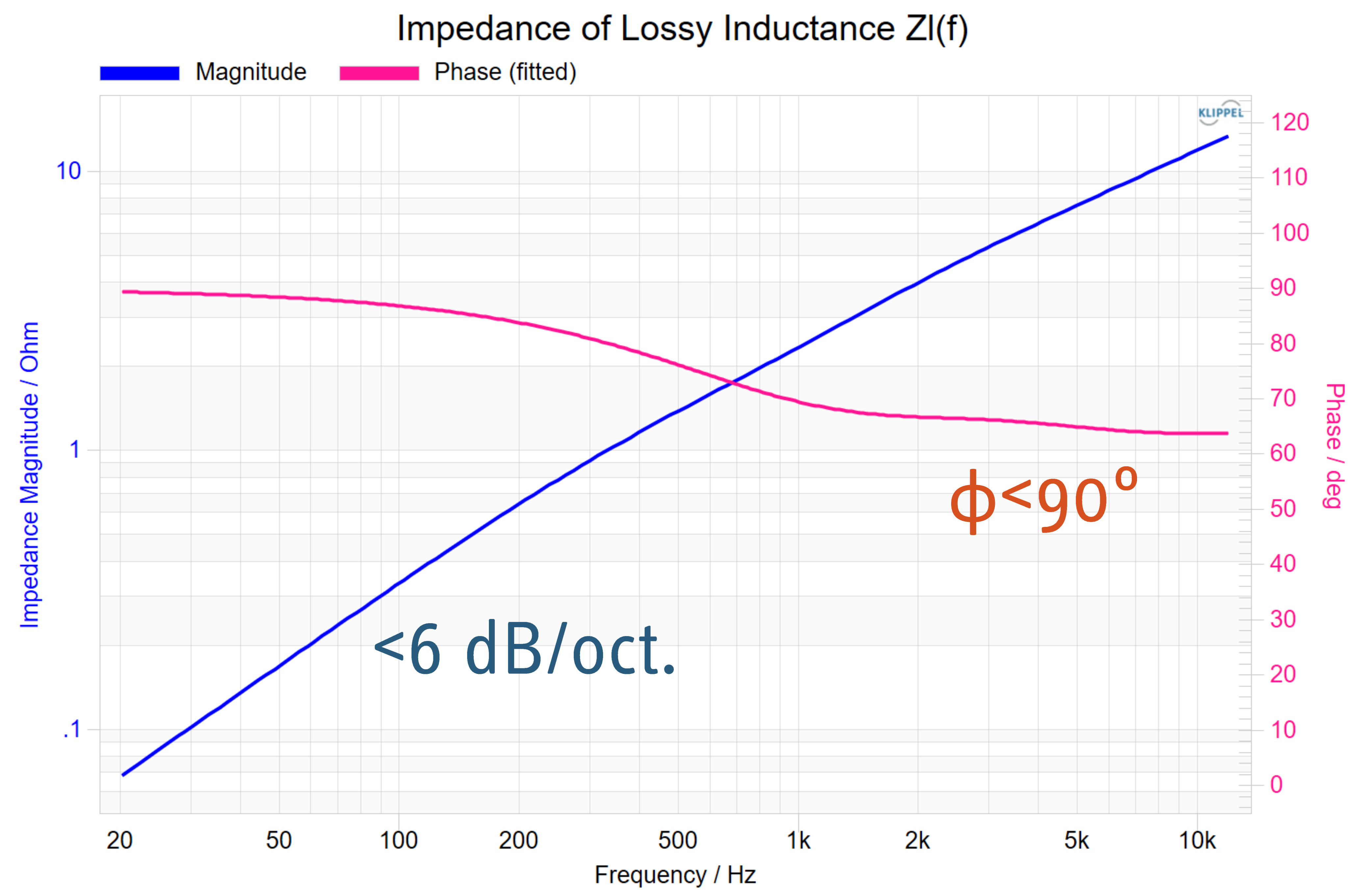
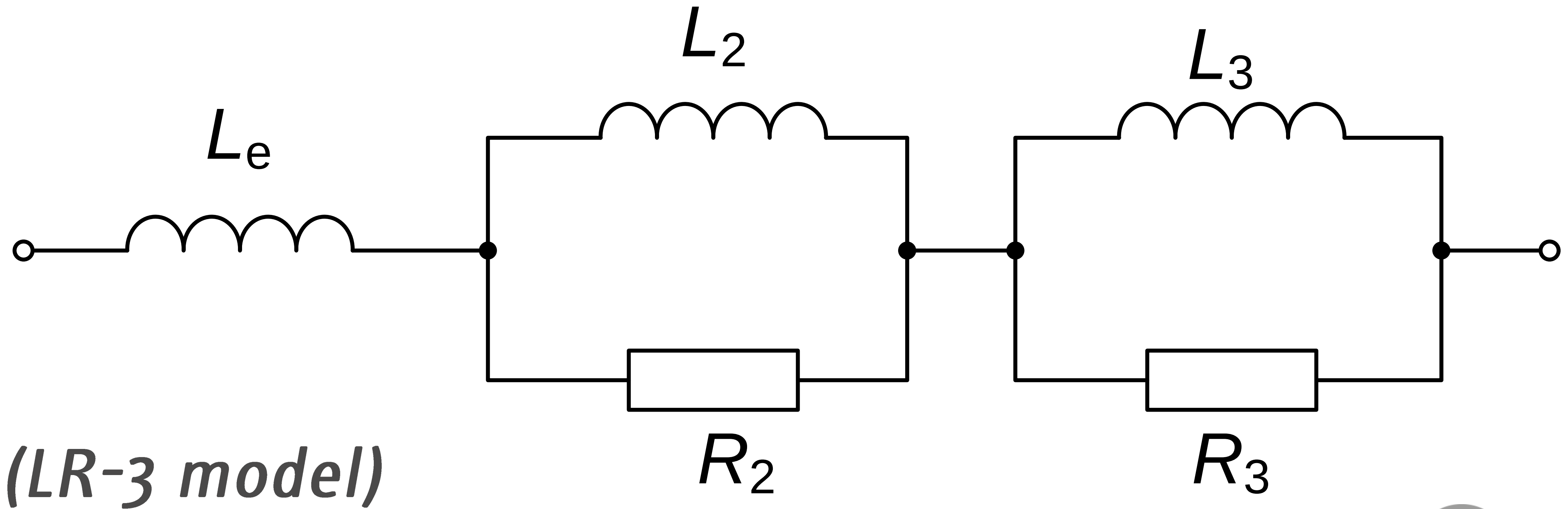
Inductance Modeling

Lossy inductance

- Real inductance depends on frequency
  - considers magnectic losses (eddy currents, skin effect, shorting rings)
- Inductance model has to consider resistive behavior
  - magnitude increases by <u>less than</u> 6dB/oct
  - phase < 90°
- LR-*N* model is used
  - versatile: can be extended by more LR elements
  - high degree of freedom compared to others (such as Leach, Wright)





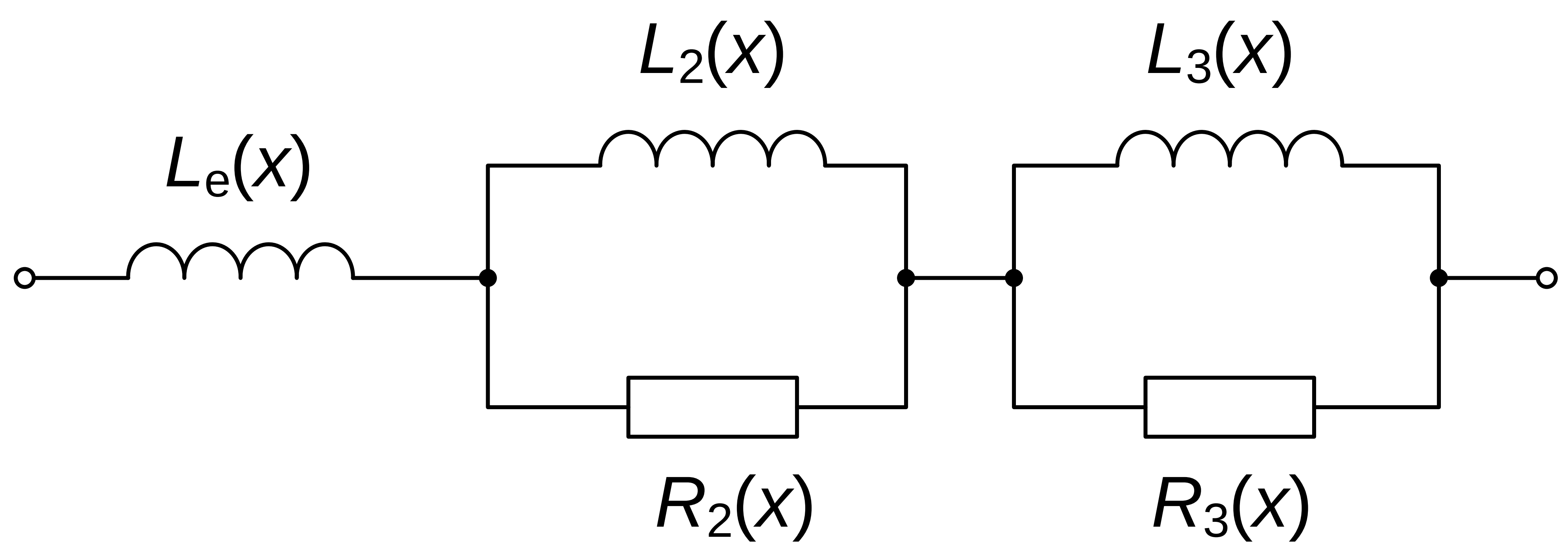
(LR-3 model)

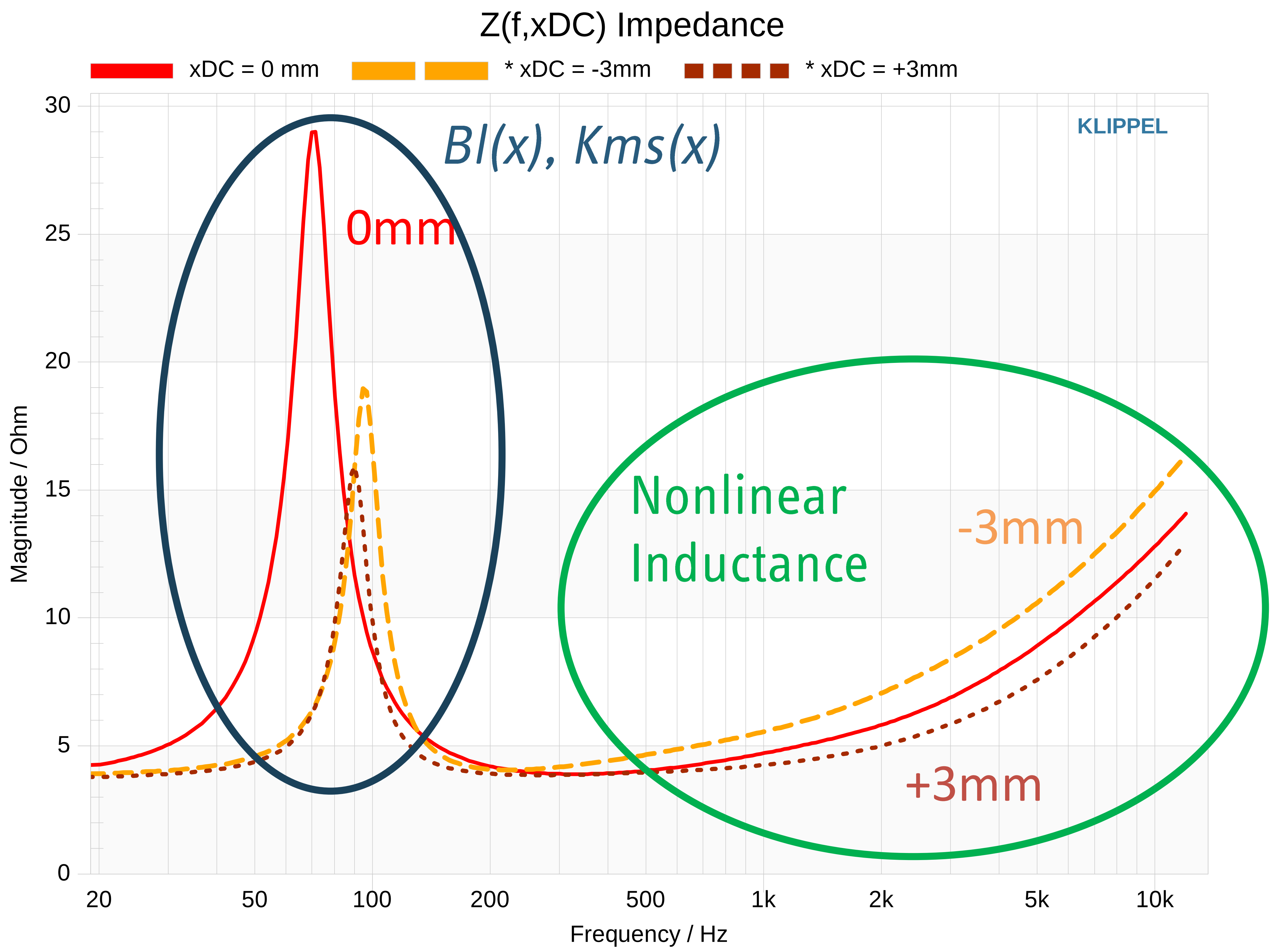
Inductance Modeling

Displacement dependancy

- Electrical Impedance changes with displacement
  - Mechanical Stiffness $K_{ms}(x)$
  - Force Factor Bl(x)
  - Voice coil self-inductance L(x,f)

- Can be modeled by a nonlinear LR-*N* model





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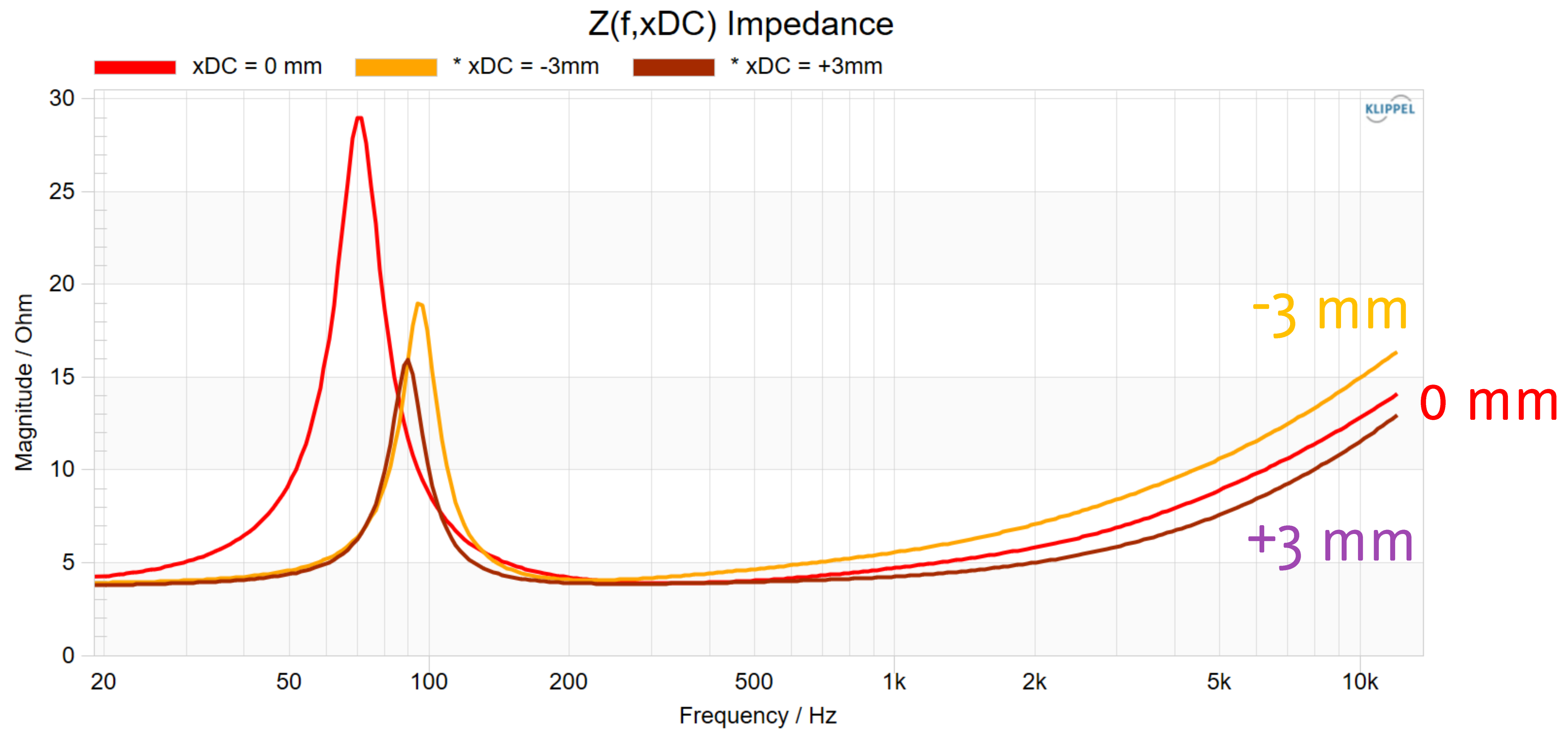
Measuring the nonlinear dynamic inductance

Point-by-point dynamic measurement

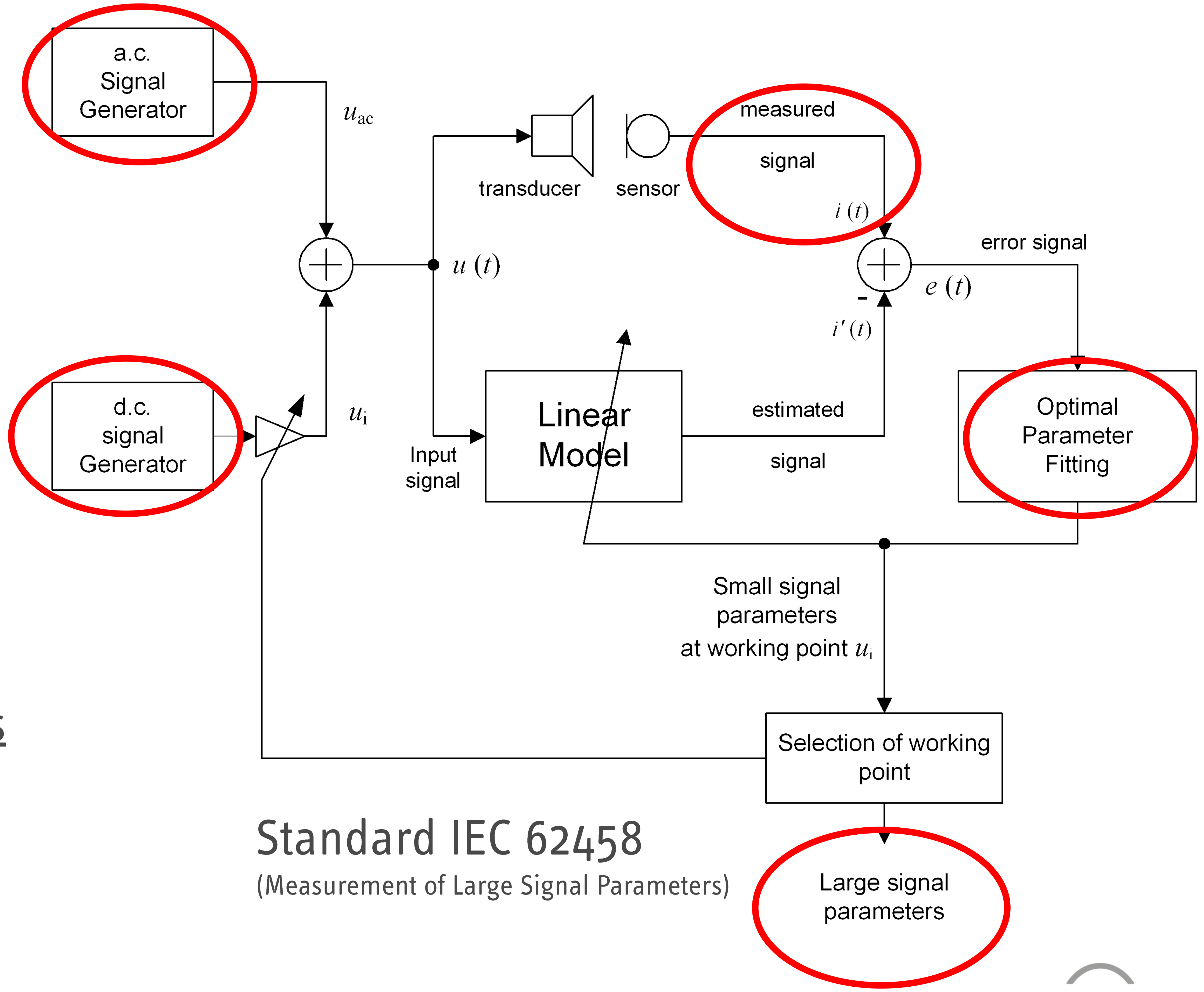
- **Small AC signal excites the driver in the audio band**
- **DC voltage shifts the voice coil to different positions**



- Small signal parameters are identified based on the impedances Z(f)=U(f)/I(f) at different positions x_{DC}:

$$\min_{p}\{||Z_{\mathrm{meas}}(x_{\mathrm{DC}}, f) - Z_{\mathrm{model}}(x_{\mathrm{DC}}, f, \mathbf{p})||^2\}$$

- parameters **p** comprise a set of LR-3 parameters



Standard IEC 62458

(Measurement of Large Signal Parameters)

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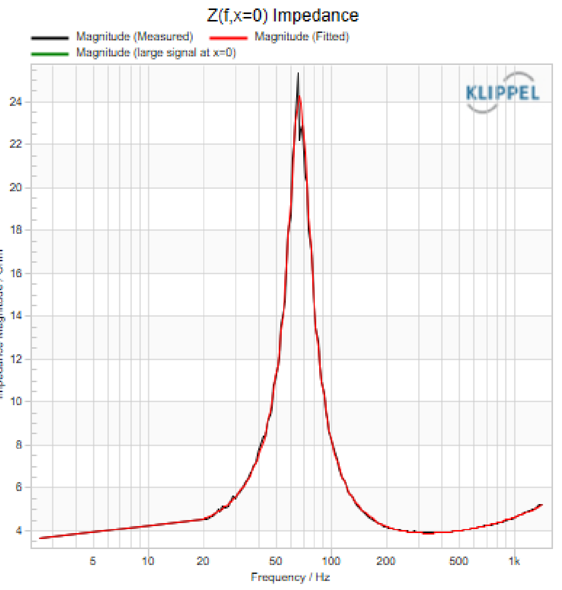
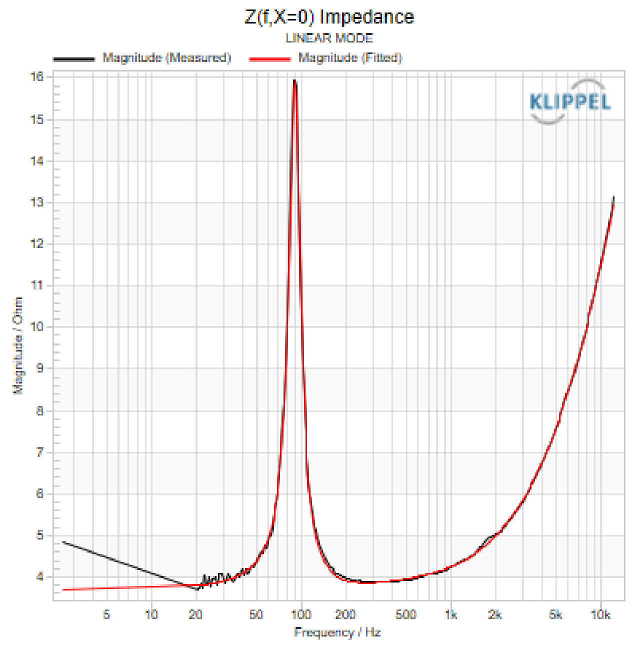
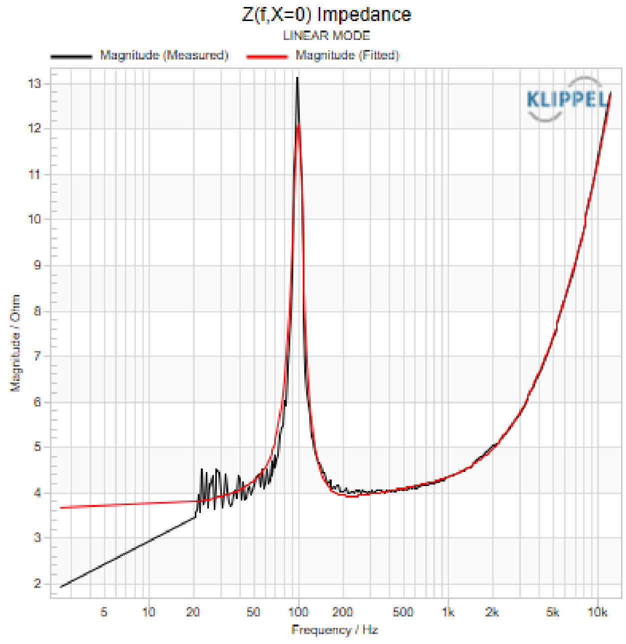
Point-by-Point Measurement

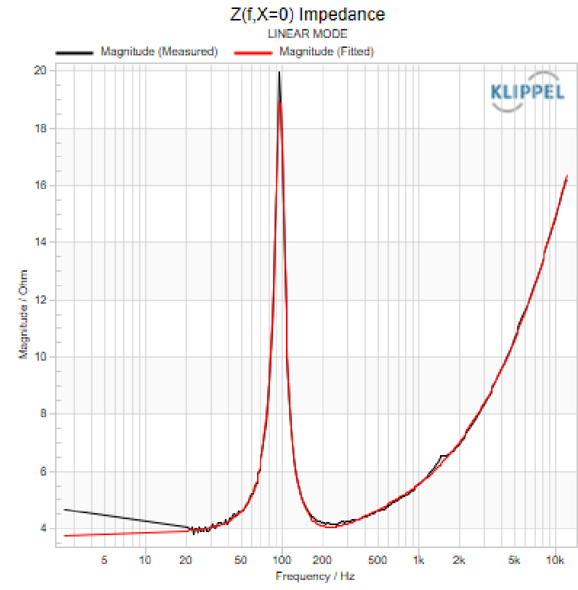
Video

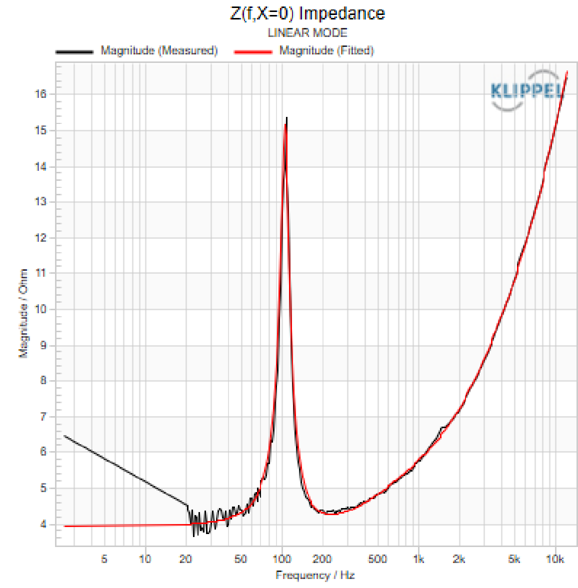
Result: Set of impedances + parameters











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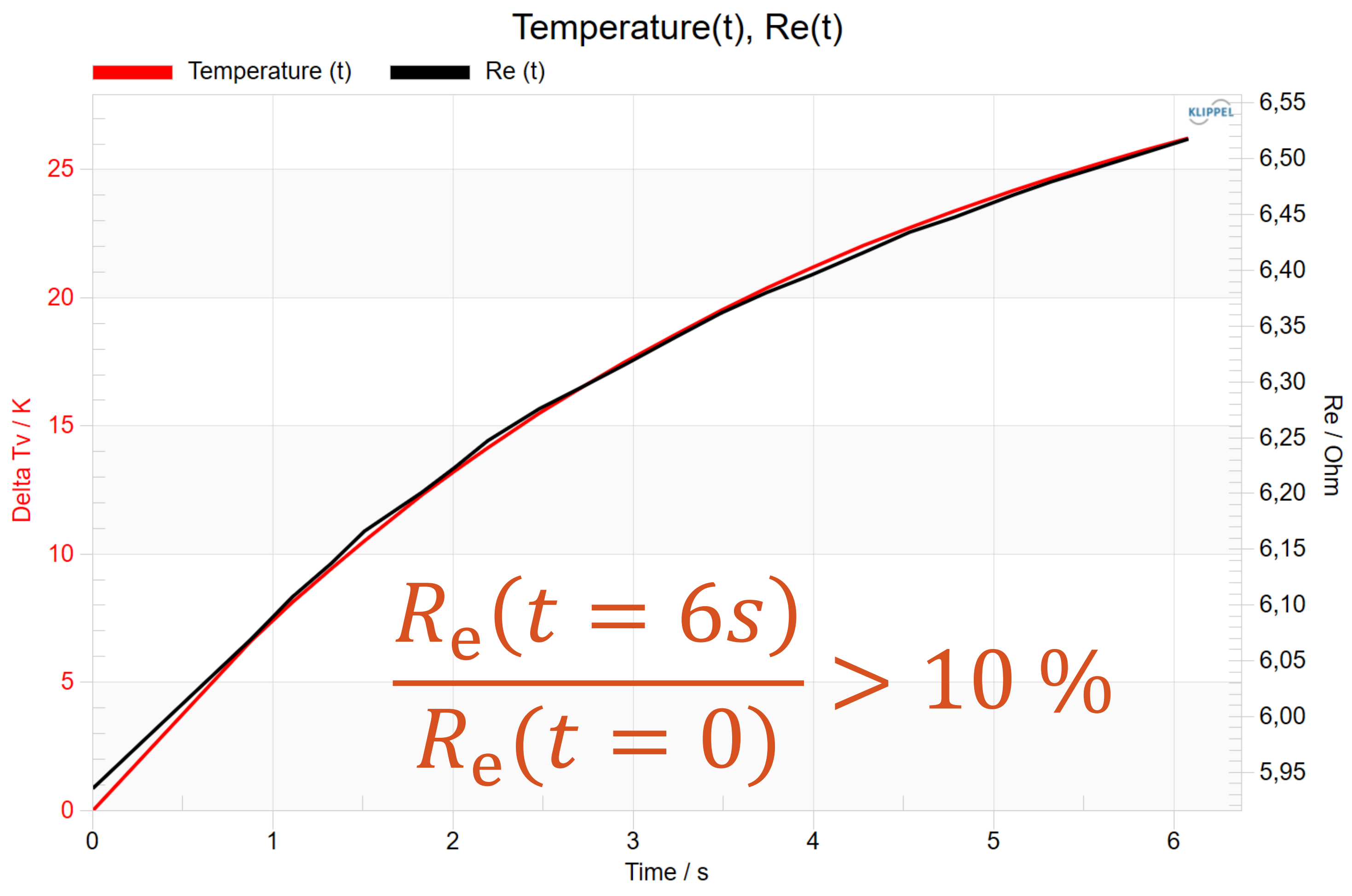
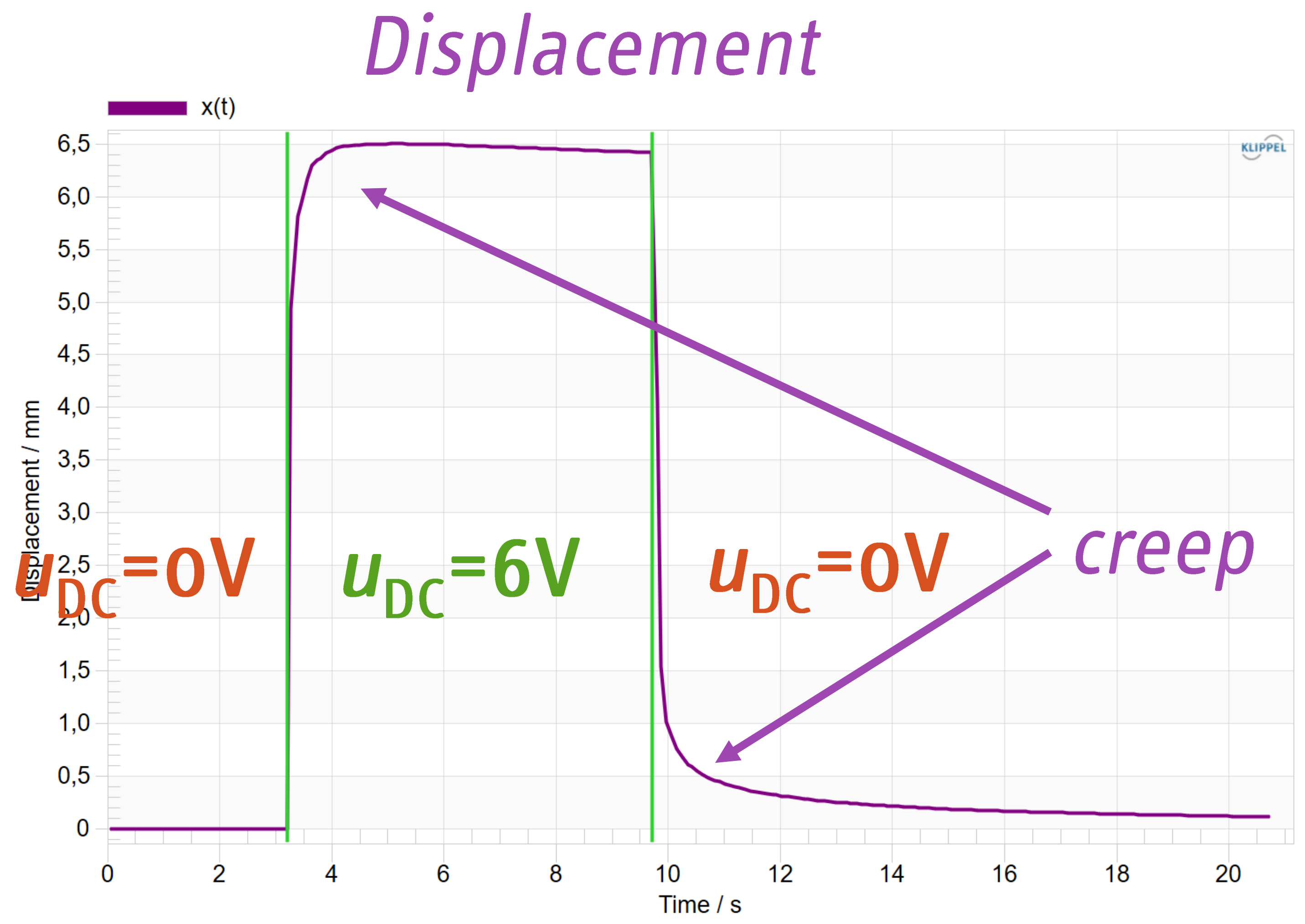
Point-by-point Measurement

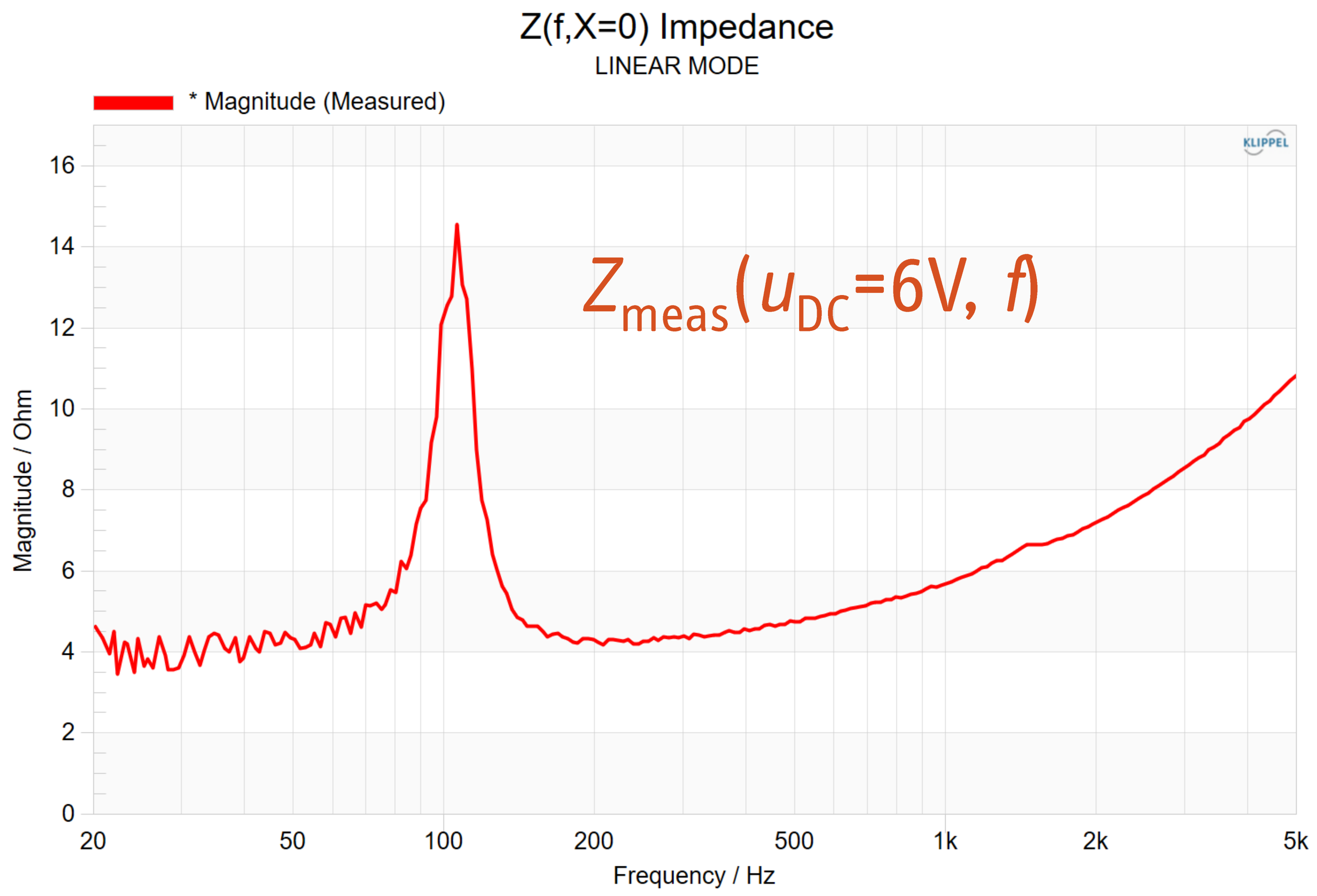
Disadvantages

During the measurement

- the voice coil temperature increases
- the mechanical creep changes the stiffness







- ➢ distorted impedance measurement
- ➢ inaccurate impedance fitting
- ➢ pre-measurement required (~10 seconds)

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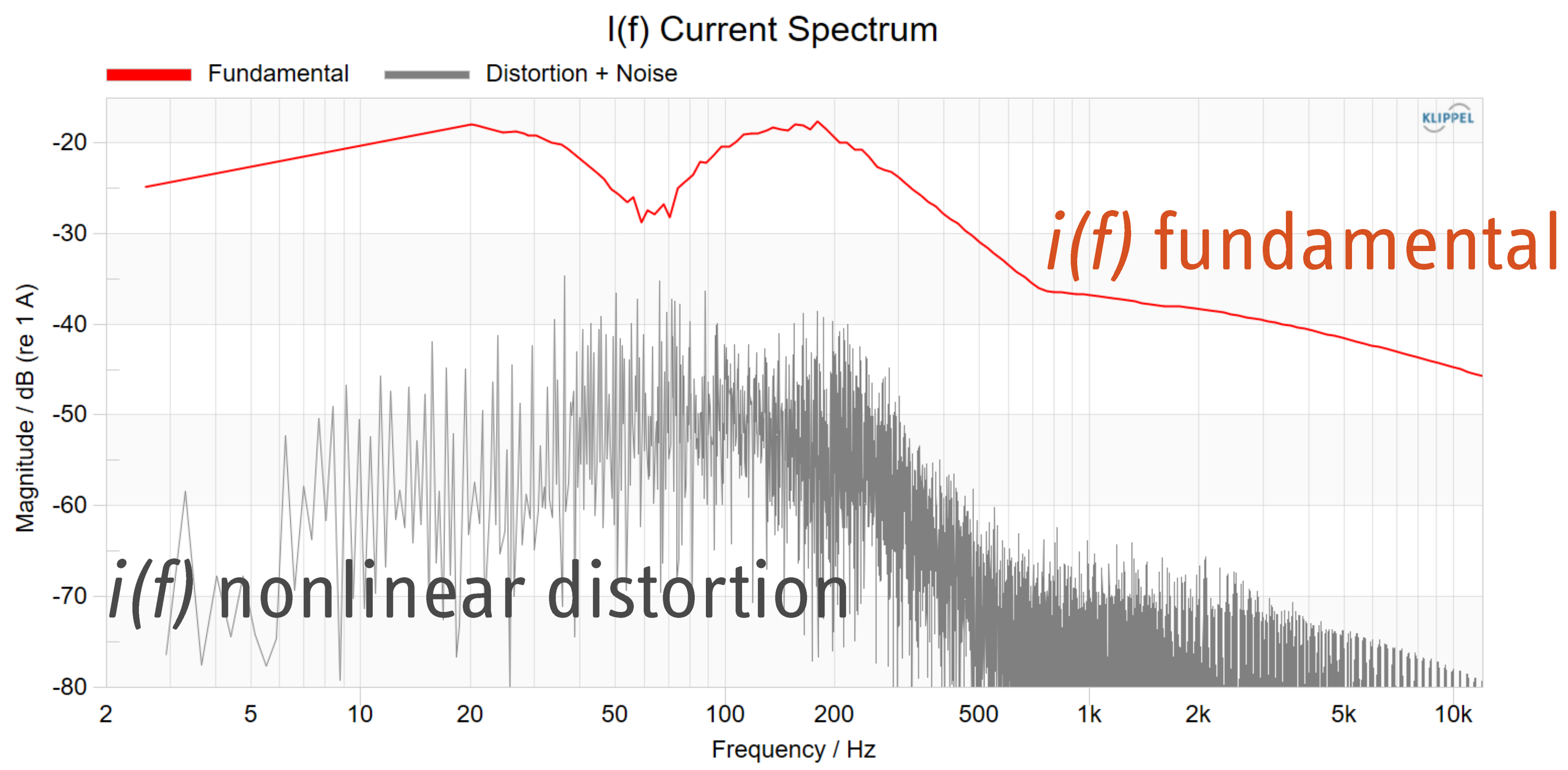
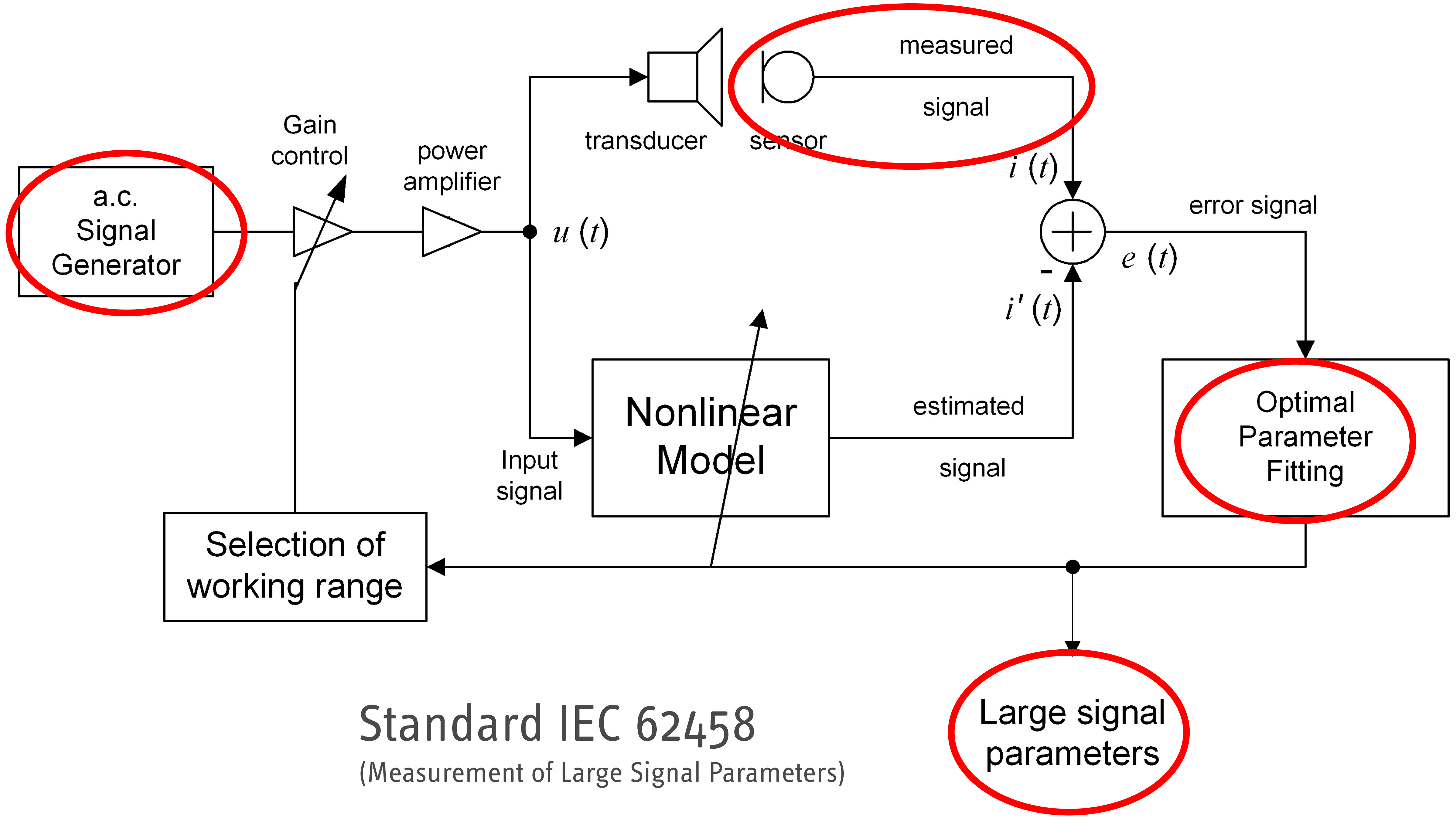
Measuring the nonlinear dynamic inductance

Full Dynamic Measurement

- **Transducer is excited by a multi-tone signal of large amplitude**
- **Only a single measurement is required**
- **Electrical current and voltage is measured**





- Main information is found in the electrical current
- Nonlinear optimization problem:

$$\min_{p}\{||i_{\text{meas}} - i_{\text{model}}(\mathbf{p})||^2\}$$

- **p** comprises the nonlinear LR-3 model parameters

Standard IEC 62458
(Measurement of Large Signal Parameters)

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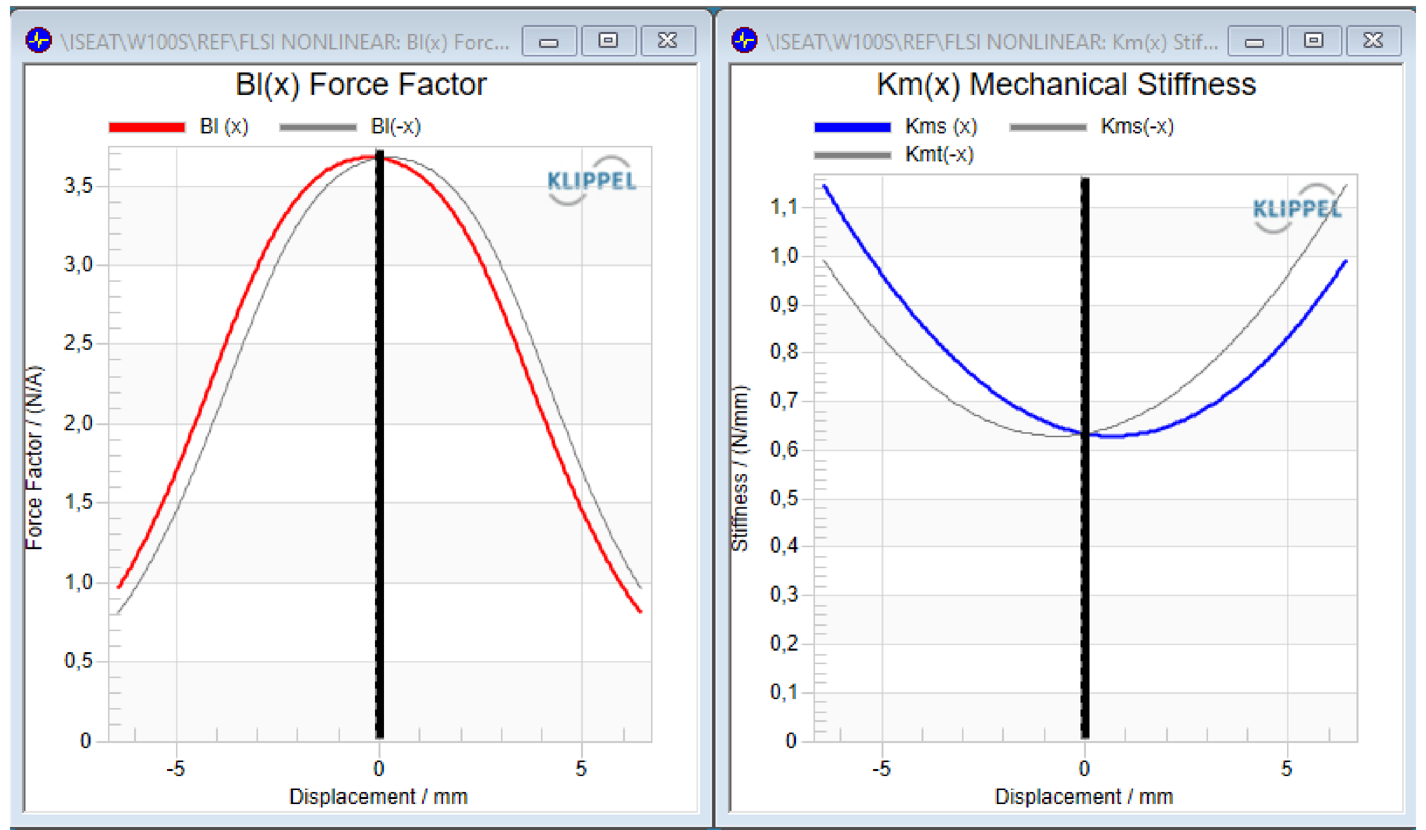
Full Dynamic Measurement

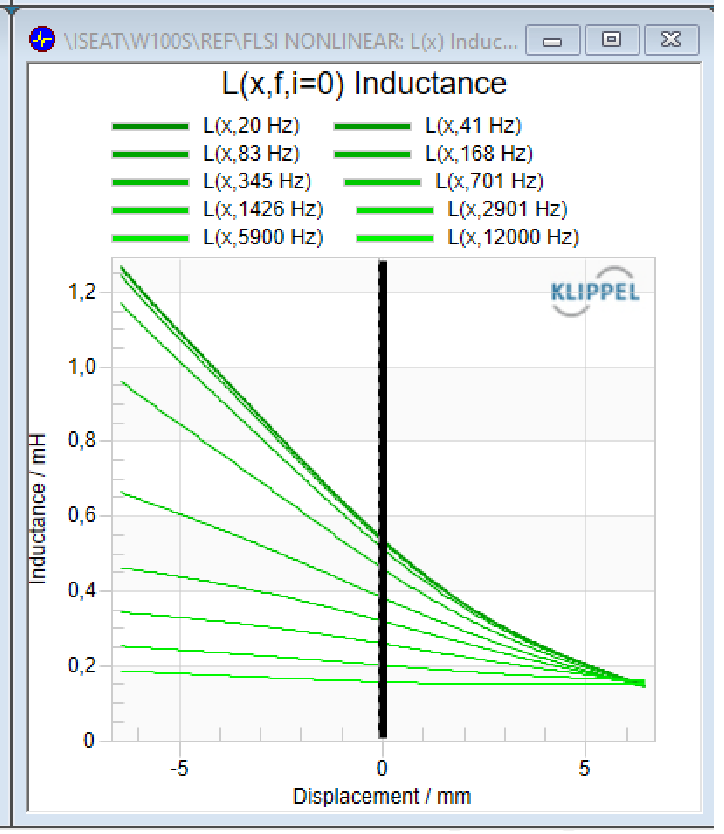
Video

Result: Linear and Nonlinear Parameters



\ISEAT\W100S\REF\FLSI NONLINEAR: Linear Par...

Symbol	Large + Warm[2]	Large + Cold[3]	Small Signal[1]
Parameters at x=0			
R_e	3.81	3.67	3.67
f_s	53.2	53.2	70.9
Q_{ts}	0.46	0.44	0.61
Q_{es}	0.53	0.51	0.70
Q_{ms}	3.24	3.24	5.16
Bl	3.68	3.68	3.65
$(Bl)^2/R_e$	3.55	3.69	3.63
M_{ms}	5.67	5.67	5.67
K_{ms}	0.63	0.63	1.13
C_{ms}	1.58	1.58	0.89
R_{ms}	0.59	0.59	0.49
L_e	0.10	0.10	0.08
L_2	0.22	0.22	0.21
R_2	0.62	0.62	1.19
L_3	0.22	0.22	0.14



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Measurement methods

Overview

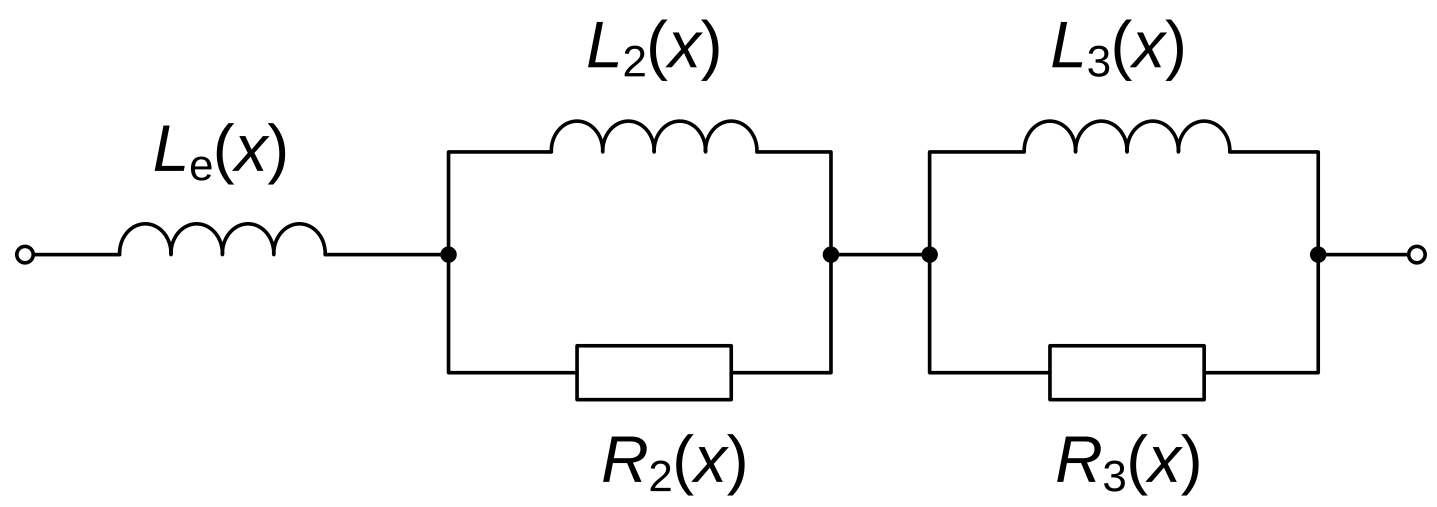
- Full dynamic measurement
  - Fast
  - Easy-to-use
  - Robust
  - Stimulus represents typical audio signals
  - Highest accuracy
  - Less heating
- Disadvantages
  - more complex fitting algorithm

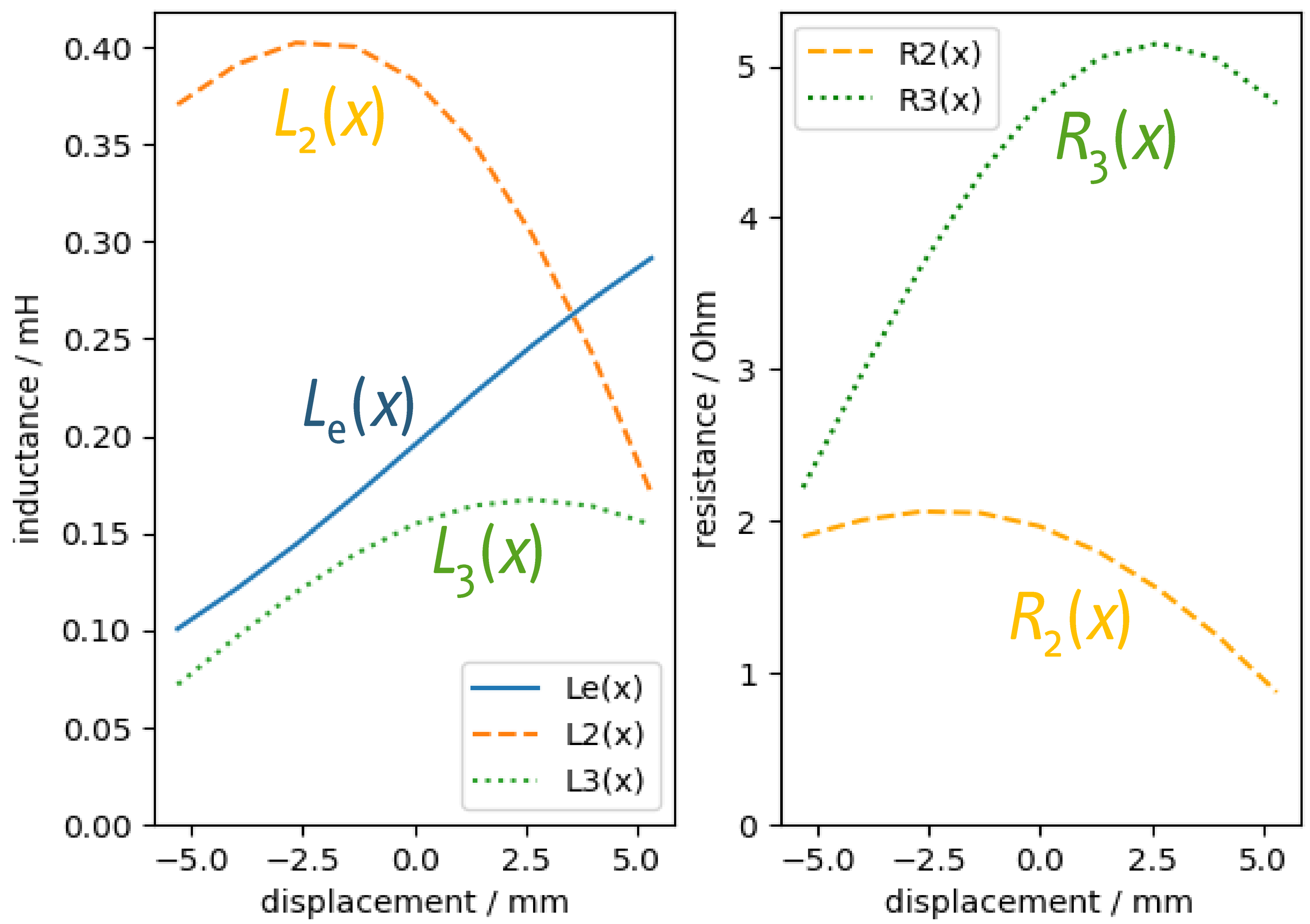
Interpretation

LR-3 model

- **Advantages**
  - Small number of parameters
  - Can be applied in simulation software
  - Can be used in real time algorithms

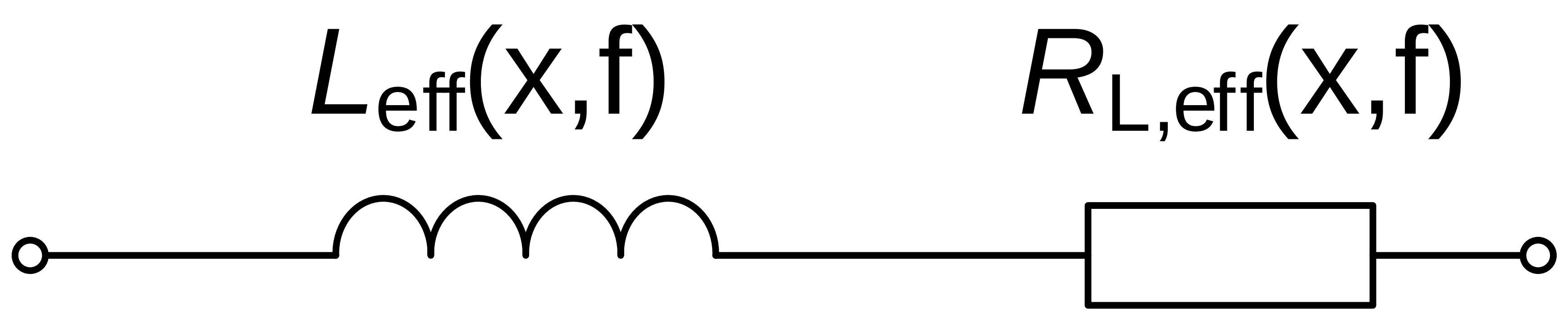
- **Difficult interpretation**
  - In which frequency range is a parameter active?
  - Which nonlinear parameter is important?
  - What is the physical cause of a parameter's characteristic?





Effective inductance parameters

Definitions

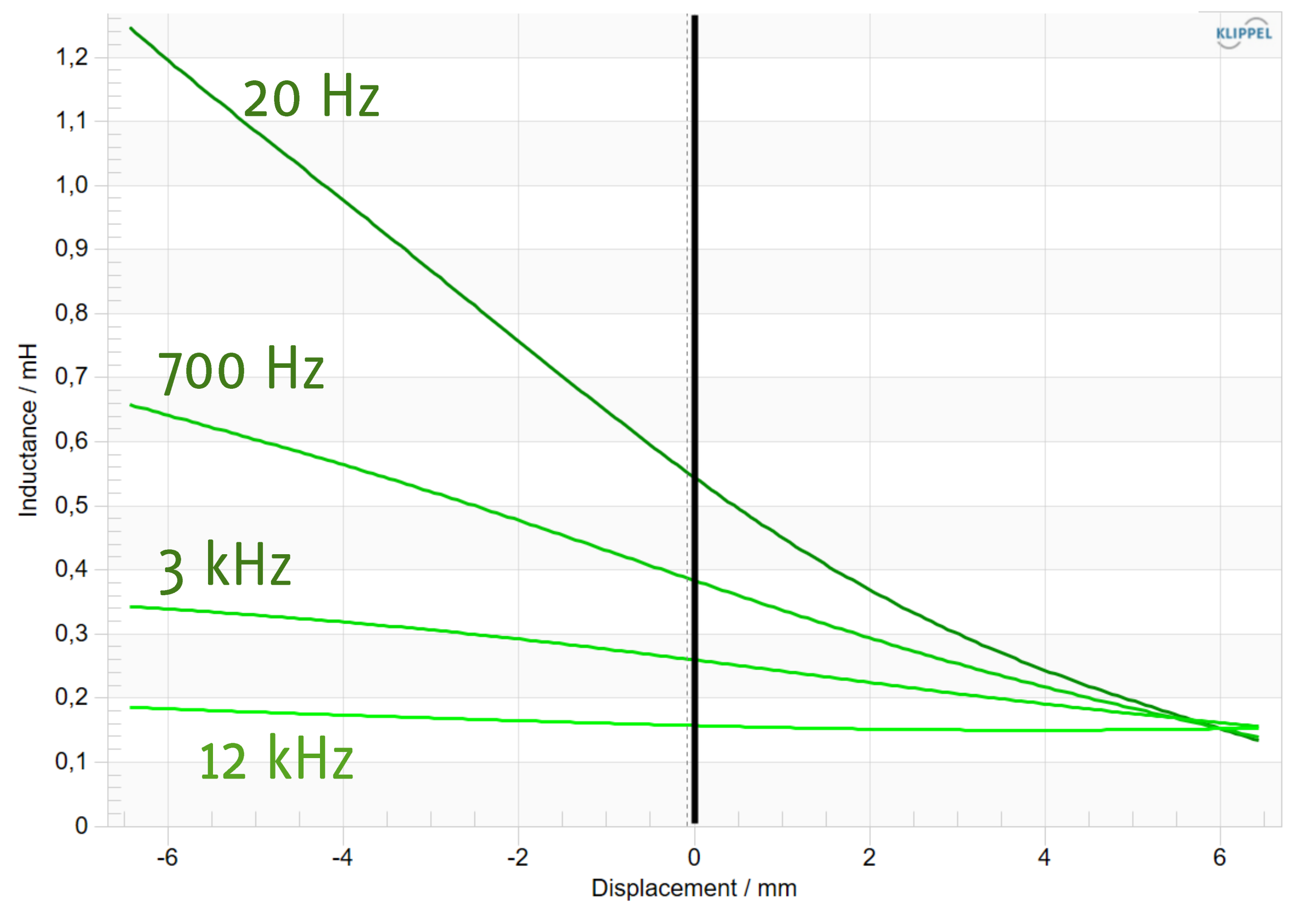


$$Z_L(x, j\omega) = j\omega\, L_{eff}(x, j\omega) + R_{L,eff}(x, j\omega)$$

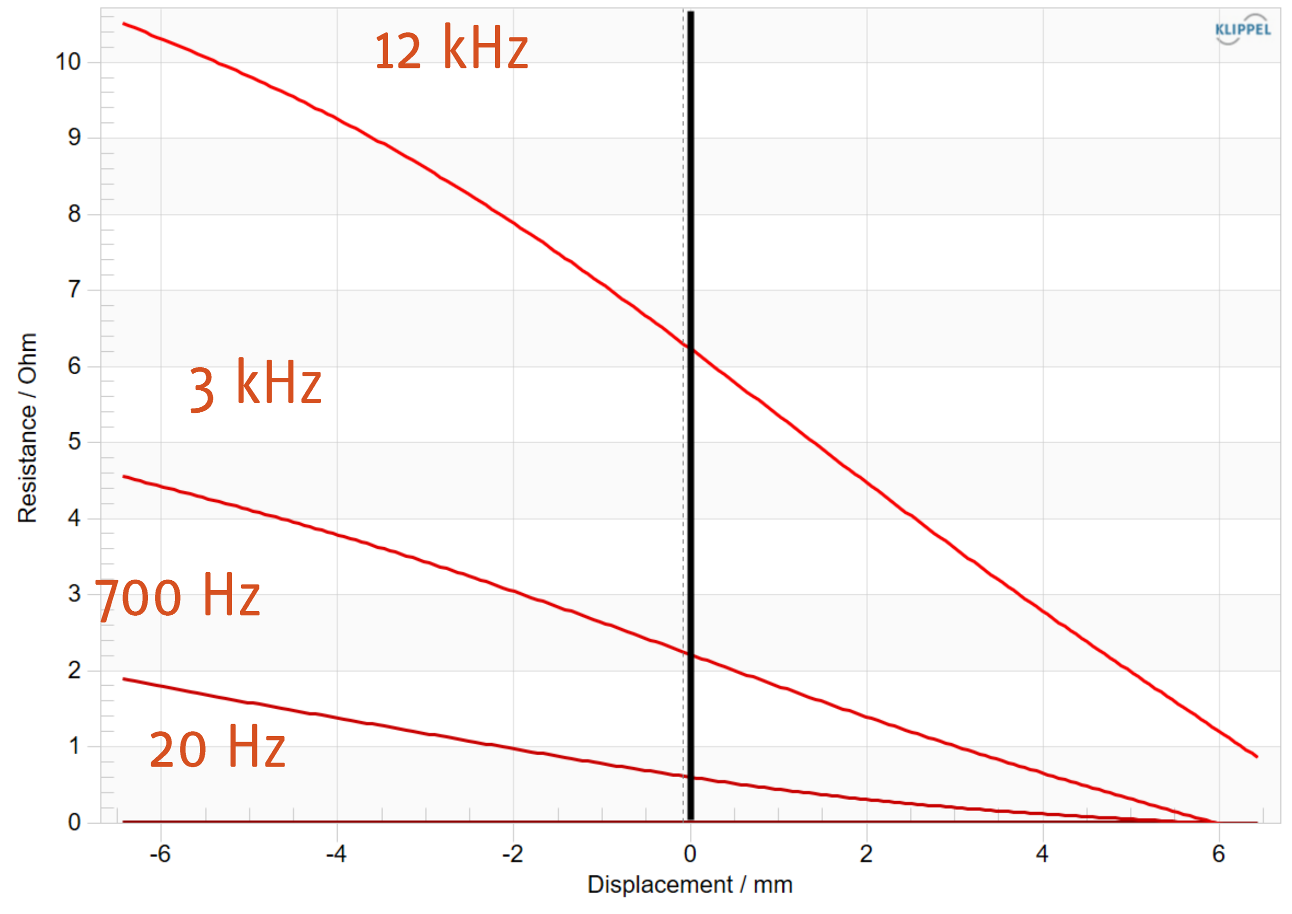
$$L_{eff}(x, f) = \frac{\Im\{Z_L(x,f)\}}{\omega}, \qquad R_{L,eff}(x, f) = \Re\{Z_L(x, f)\}$$

- L_{eff}: reactive part (conservative)
- $R_{L,eff}$: resistive part (dissipative → losses)
- Derived from the LR-N model

$L_{eff}(x, f)$



$R_{L,eff}(x, f)$



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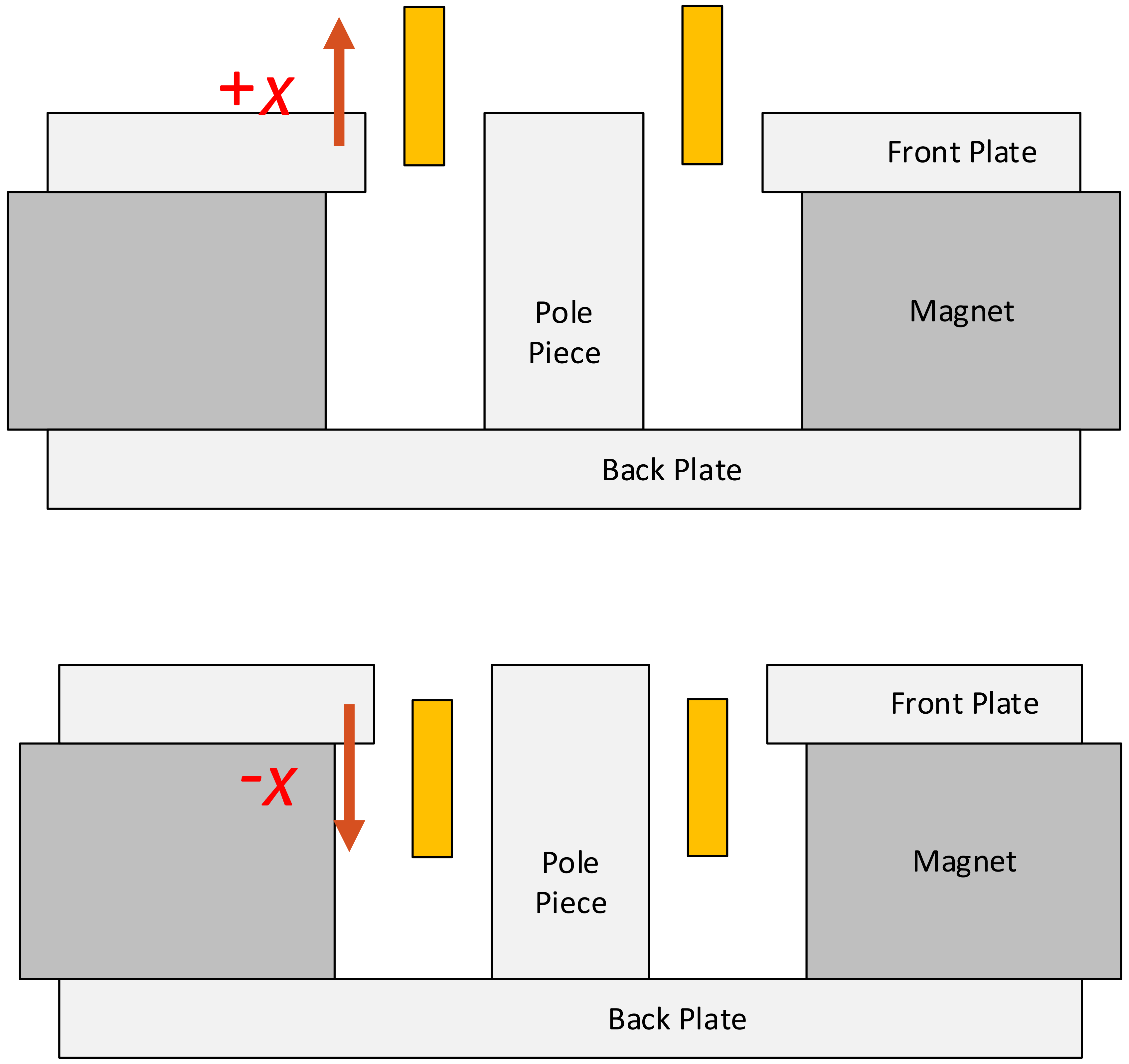
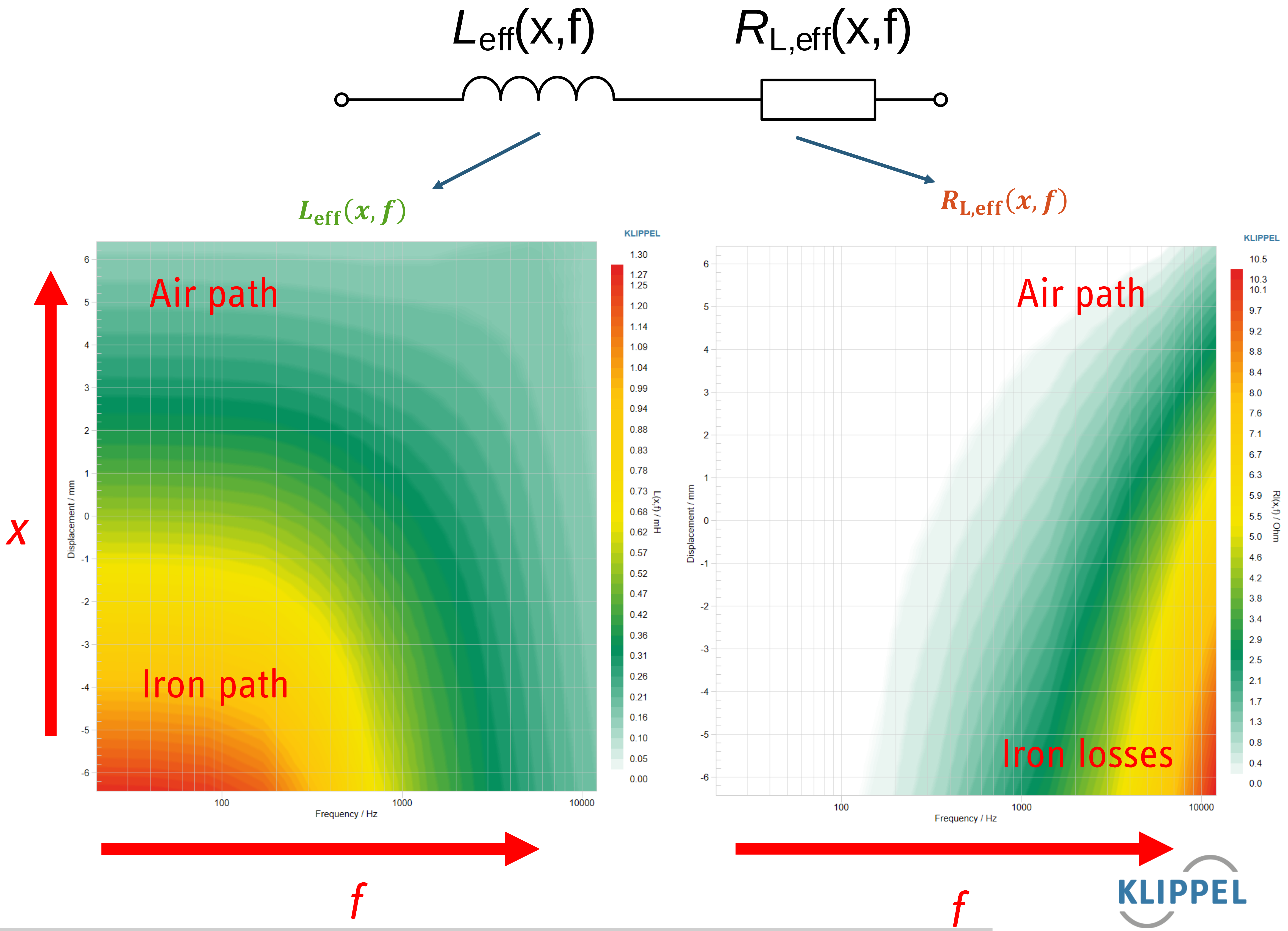
Effective inductance parameters

No shorting ring





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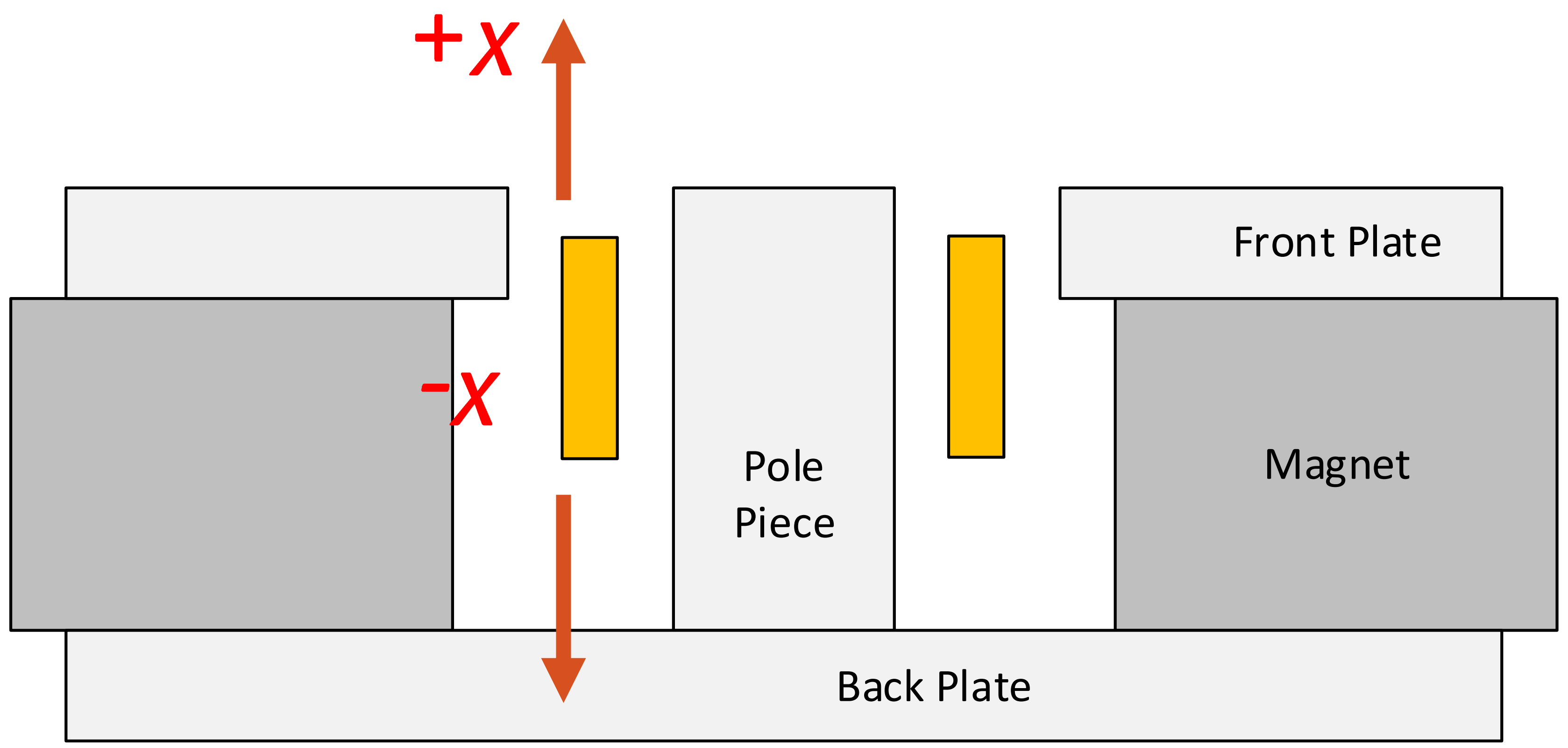
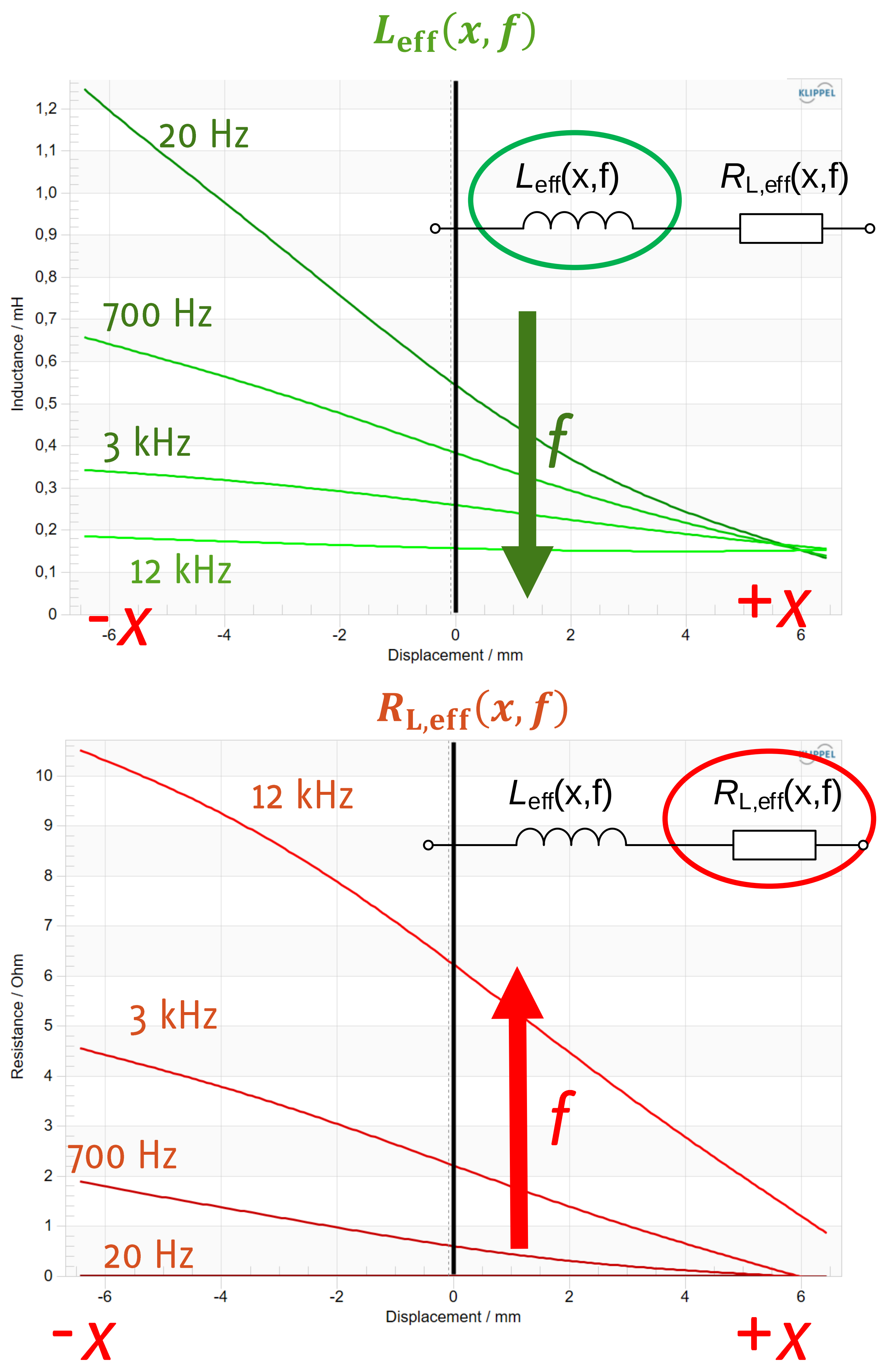
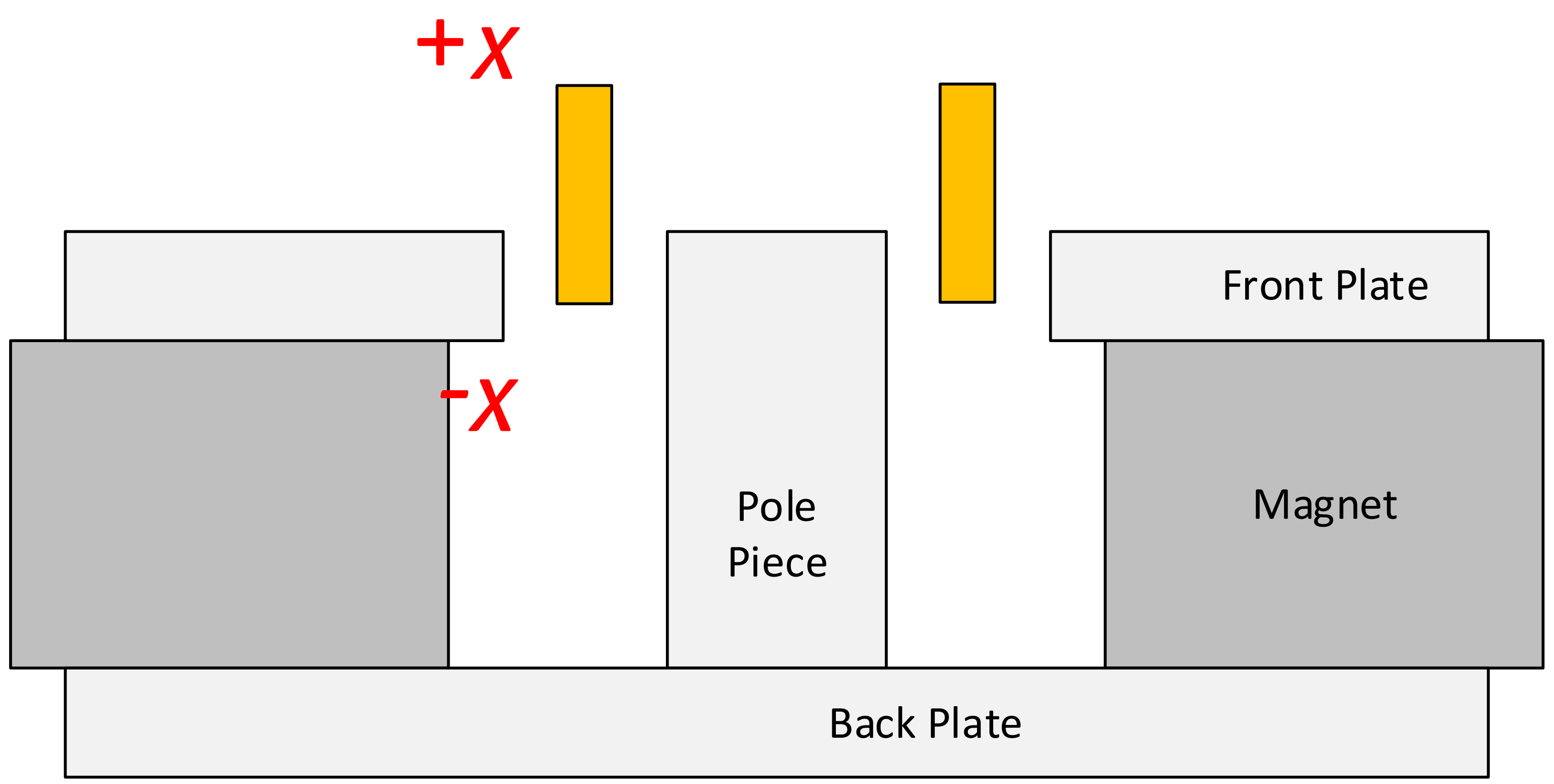
Effective inductance parameters

No shorting ring







- at low frequencies:
  - high inductance, low losses
- at high frequencies
  - high losses
  - inductance decreases but is still higher than at the air path
  - large part of the electric input power is not stored as magnetic energy but dissipated into heat

Air path:

- low inductance
- low losses
- comparable to an air coil

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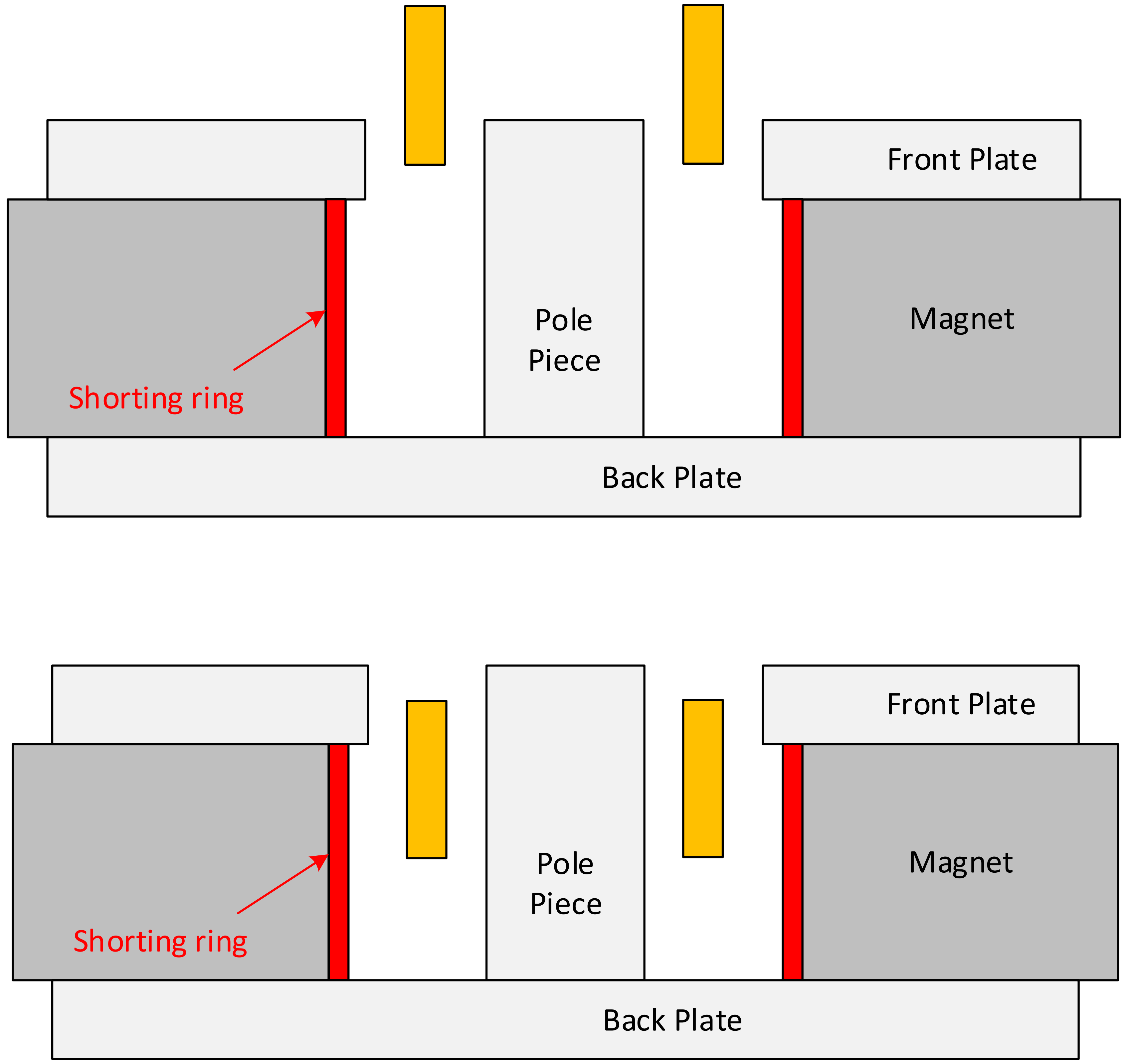
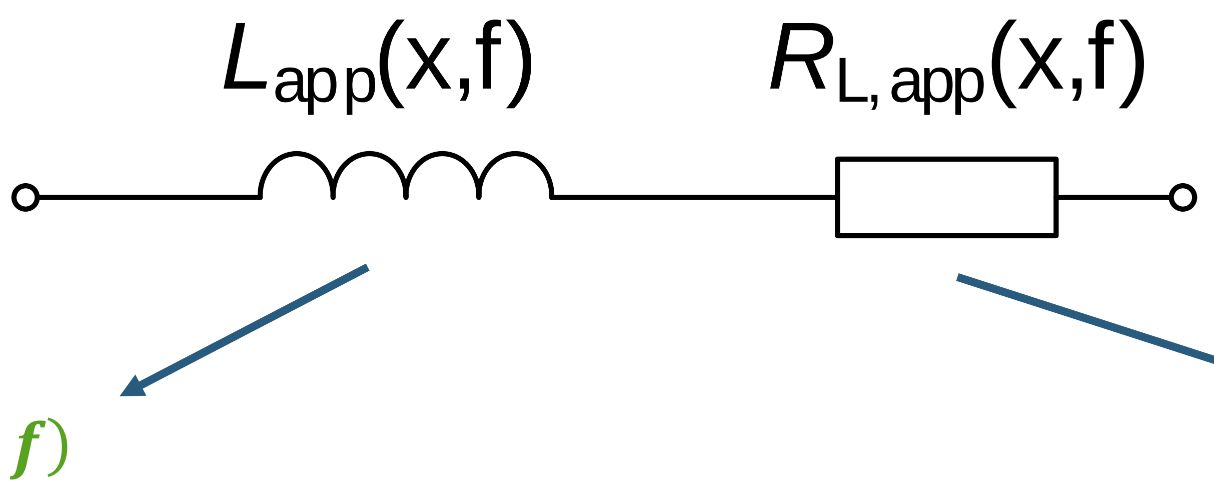
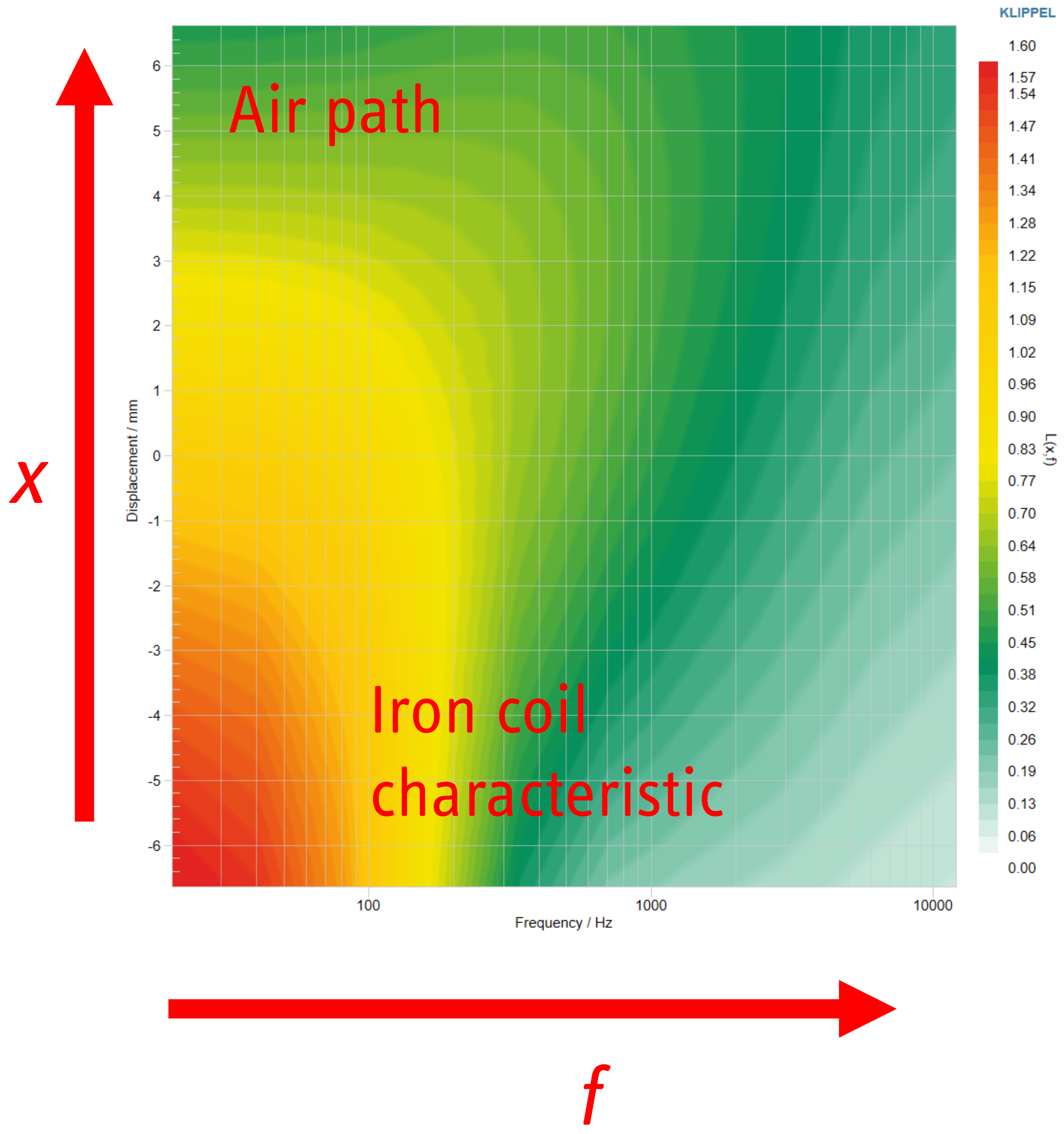
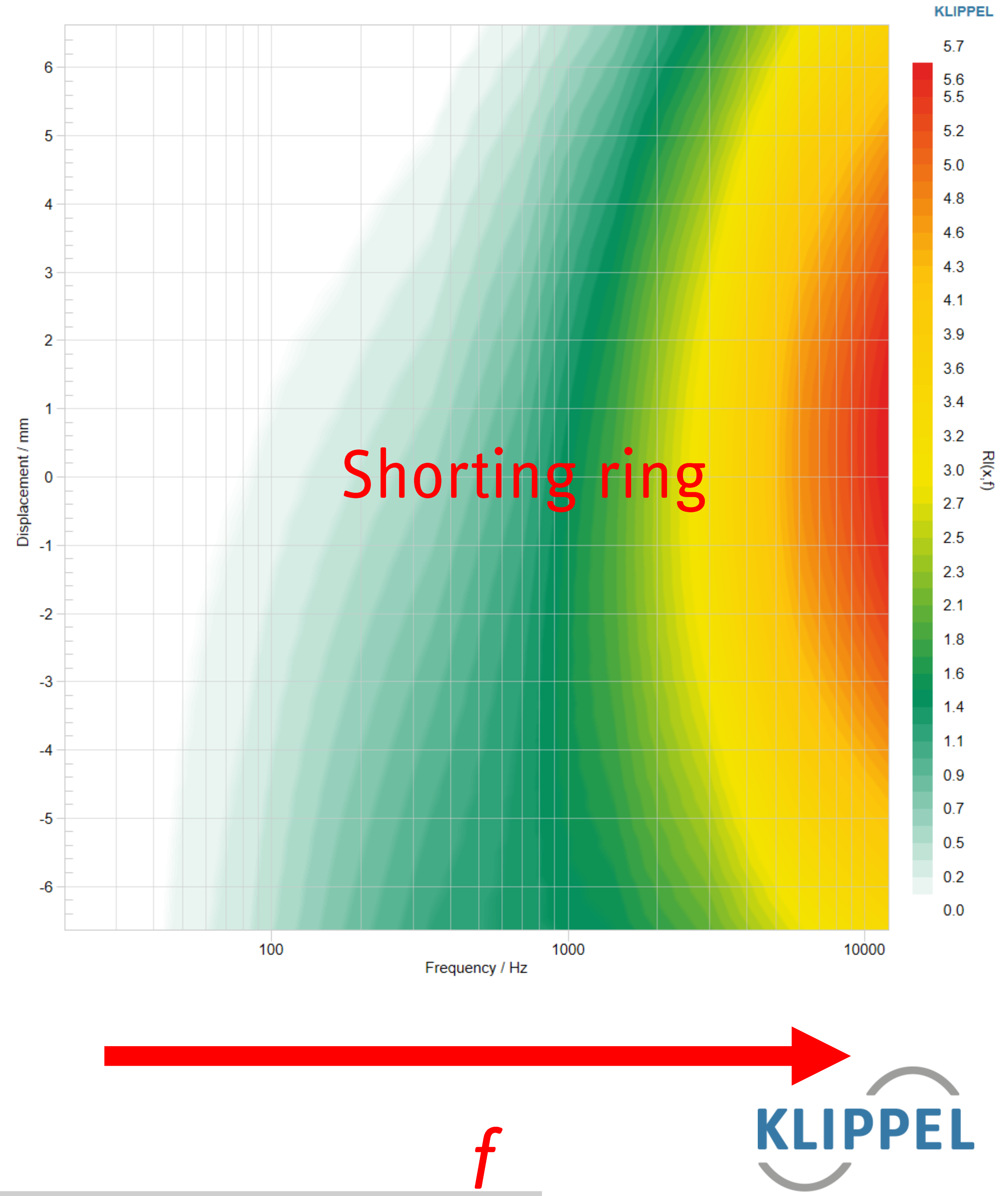
Effective inductance parameters

With shorting ring









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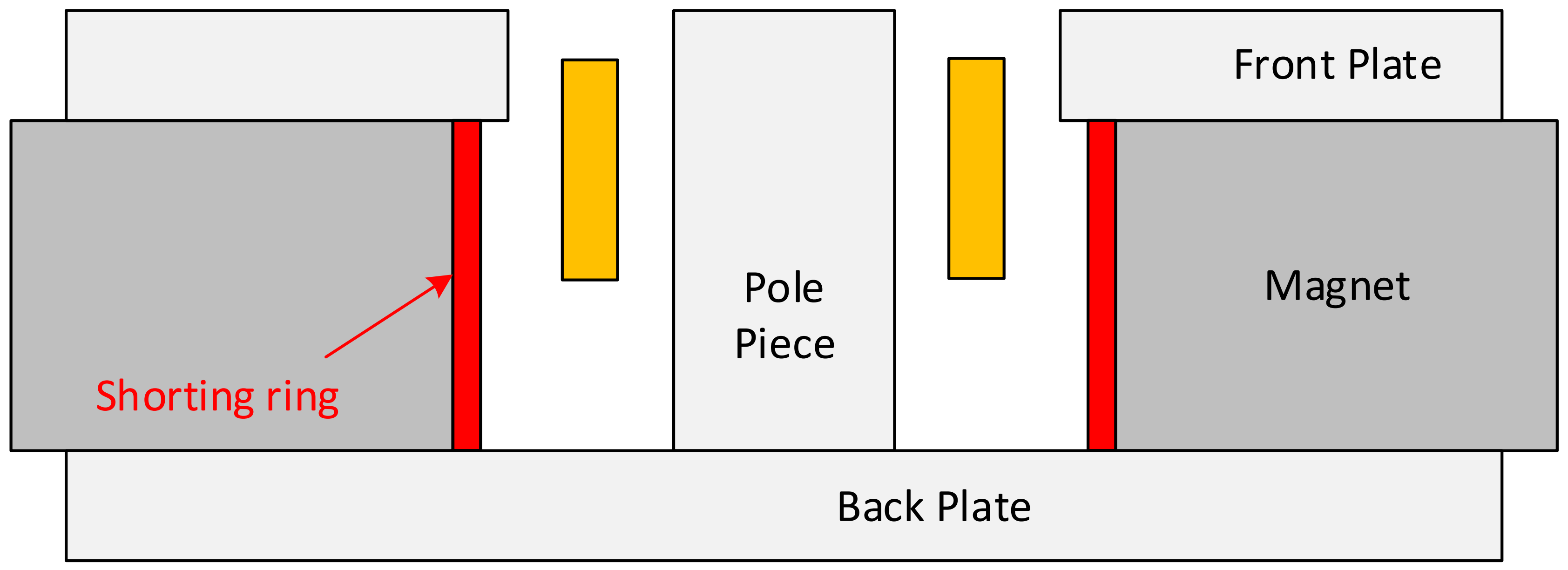
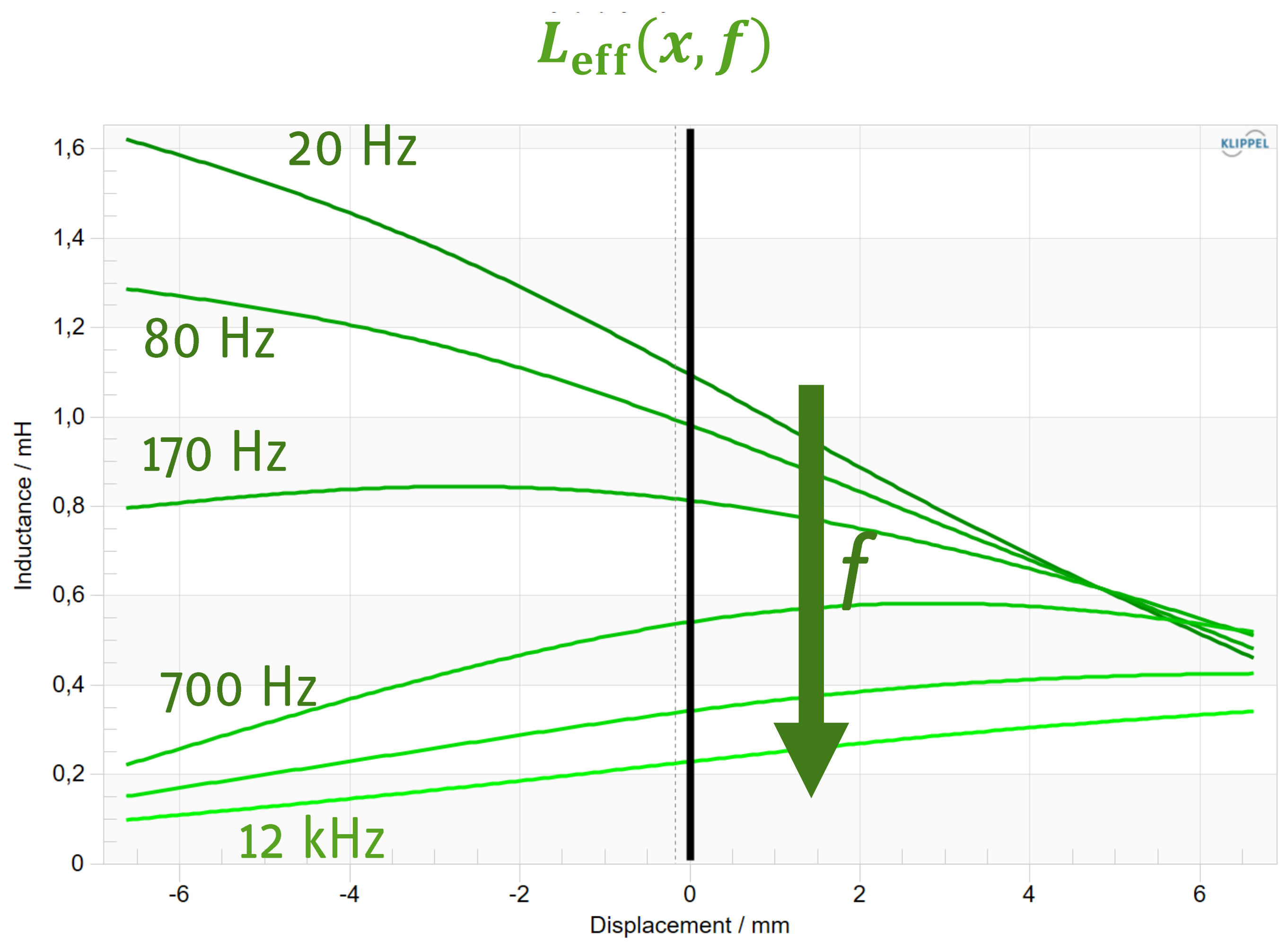
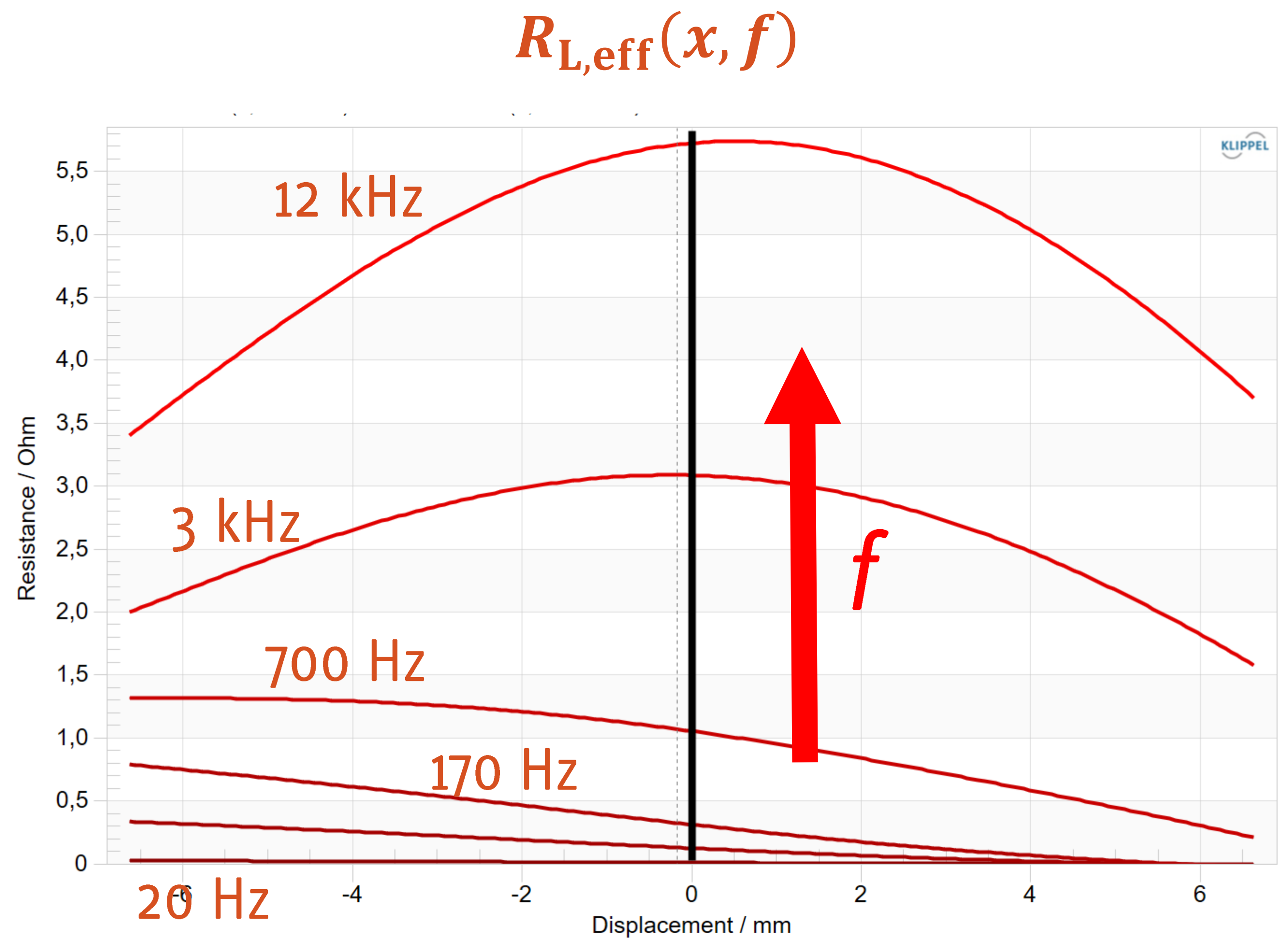
Effective inductance parameters

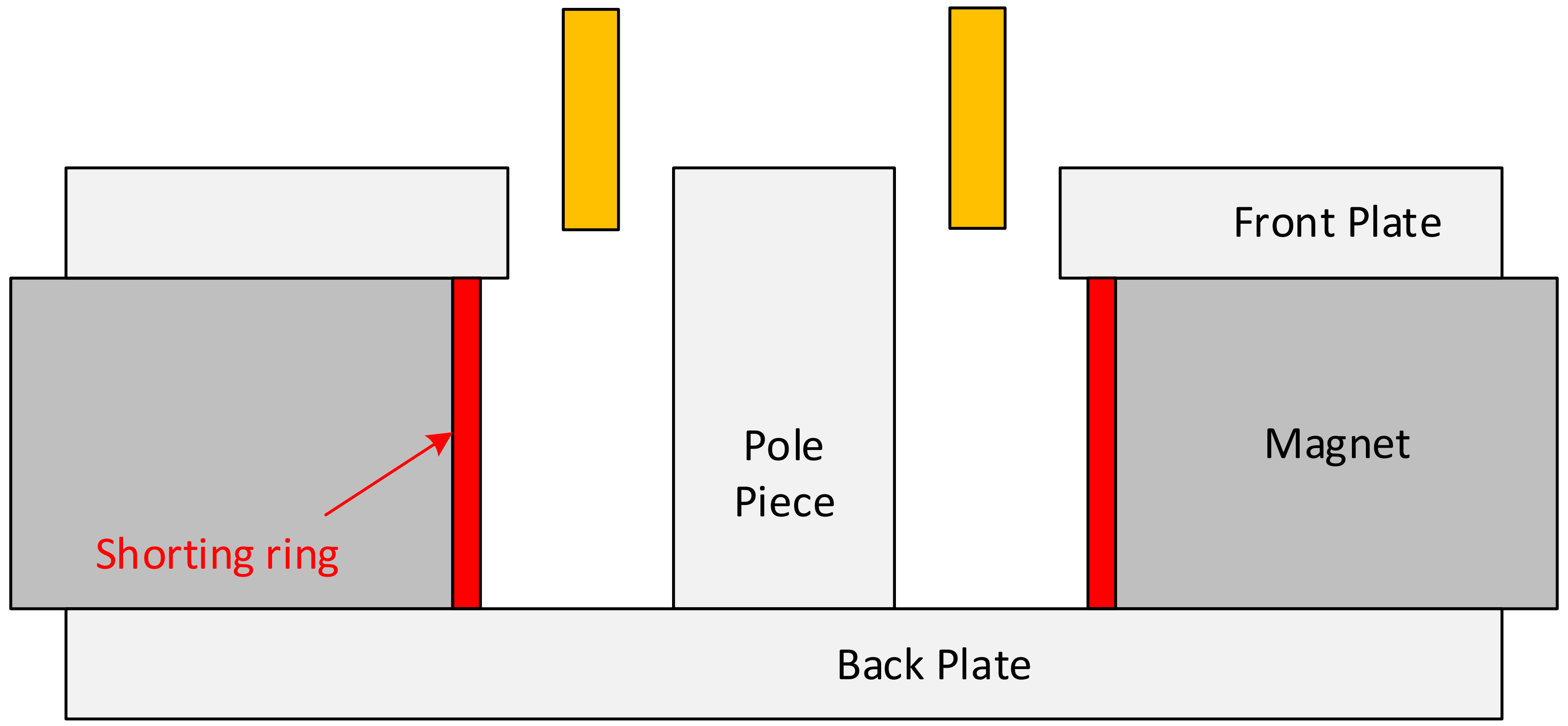
With shorting ring







- at <u>low</u> frequencies
  - comparble to transducer without shorting ring
- at <u>high</u> frequencies
  - inductance curve *tilts*
  - losses are lower than without shorting ring



Air path:

- low inductance
- low losses
- comparable to an air coil

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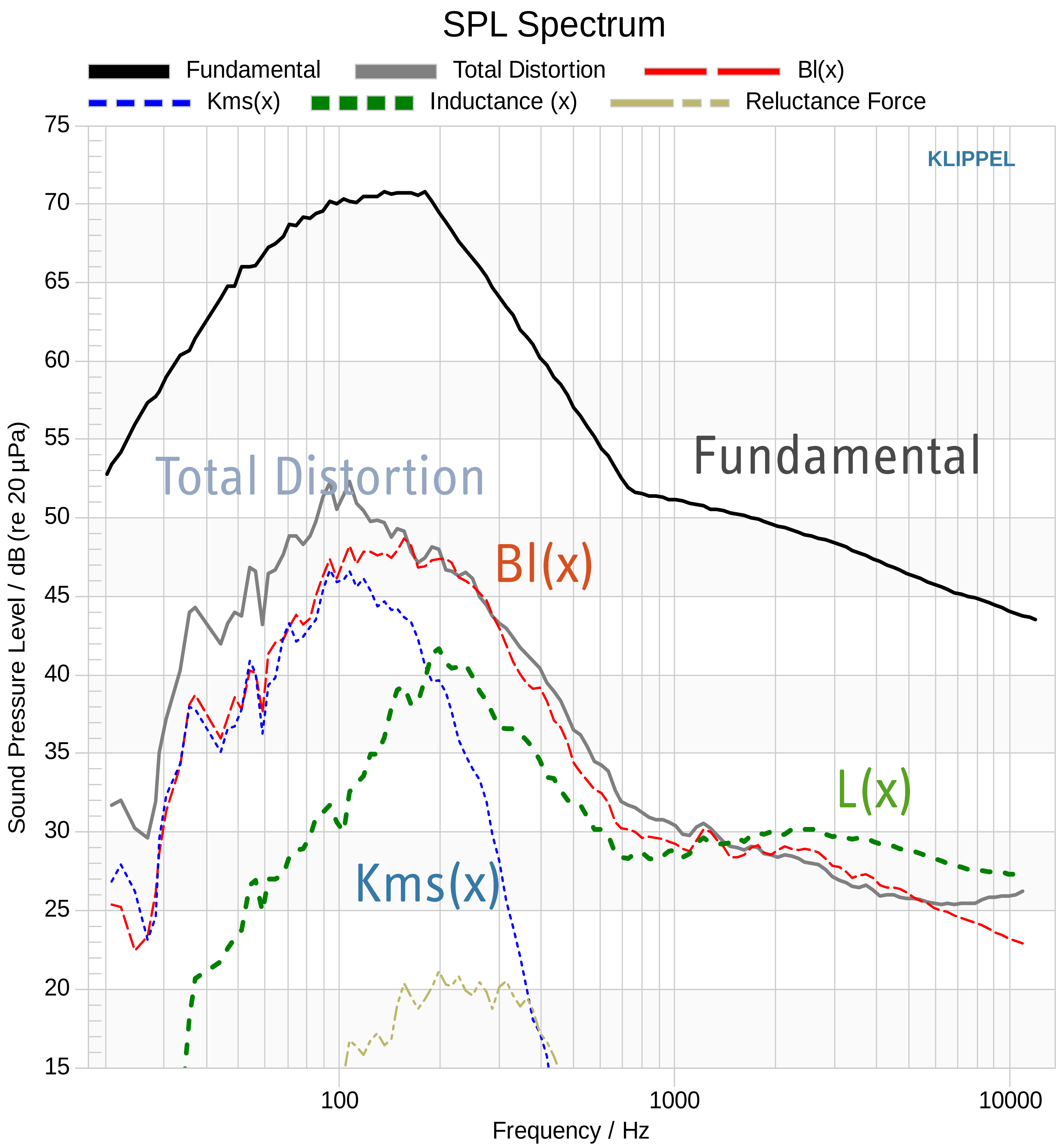
Analysis of Output Distortion

- Full dynamic measurement identifies all relevant linear and nonlinear parameters
- This allows calculating the nonlinear distortion caused by every element
- Shows the dominant nonlinear distortion
- Enables to focus on the most relevant elements for improving the loudspeaker
- Allows to compare prototypes with and without shorting material
- Simplifies evaluating optimal shorting material postitioning



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Key takeaways

- Full dynamic measurement is superior to the point-by-point measurement
  - Best accuracy
  - Easy to use
  - Short measurement time
  - Exploits nonlinear distortion (harmonic and intermodulation) for parameter identification
- LR-N model is well suited for simulations and active compensation
  - Allows direct reluctance force calculation
- Effective elements $L_{eff}(x,f)$ and $R_{L,eff}(x,f)$
  - simplify interpretation
  - can be compared and verified with FEA (COMSOL, FEMM, ...)
- Distortion Analysis
  - decomposition of the nonlinear distortion components
  - high diagnostic value to evaluate and inprove the motor design

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