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VALIDATING NONLINEAR TRANSDUCER MOTOR SIMULATIONS WITH MEASUREMENTS

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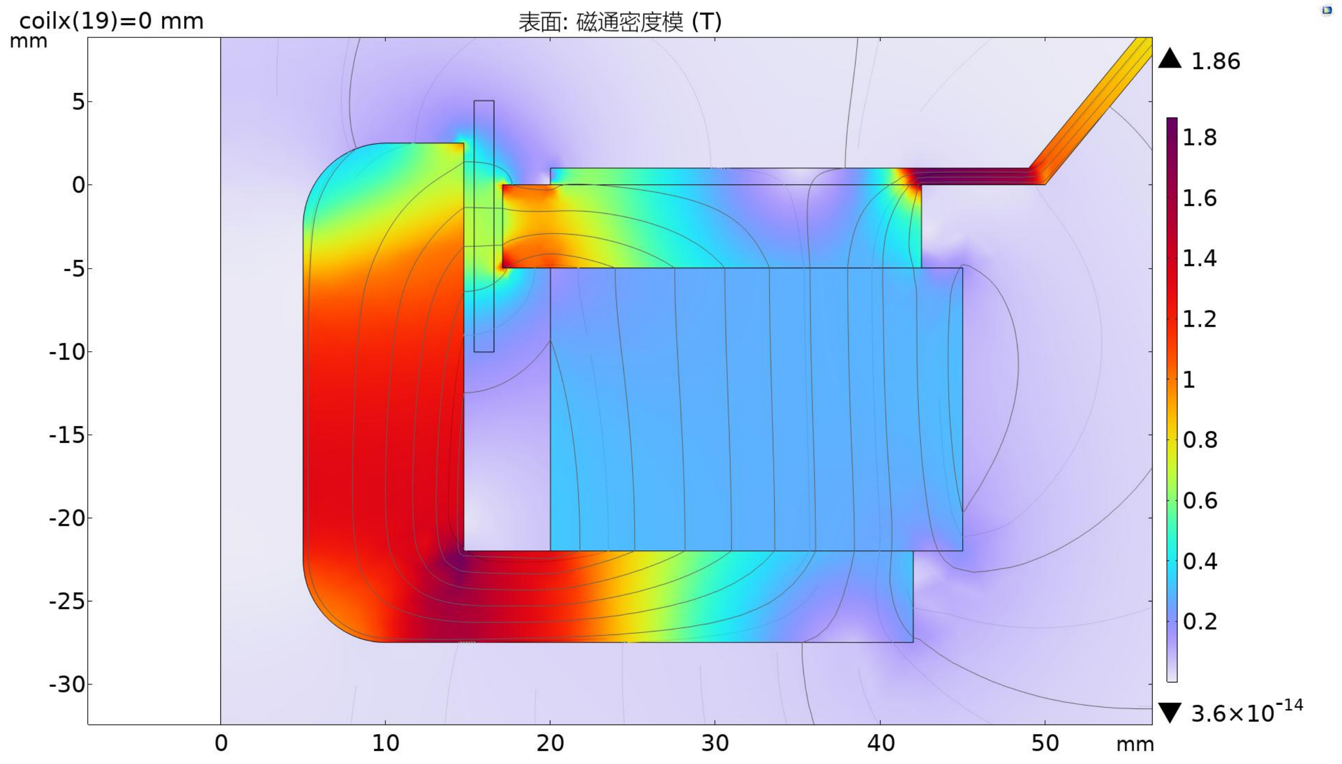
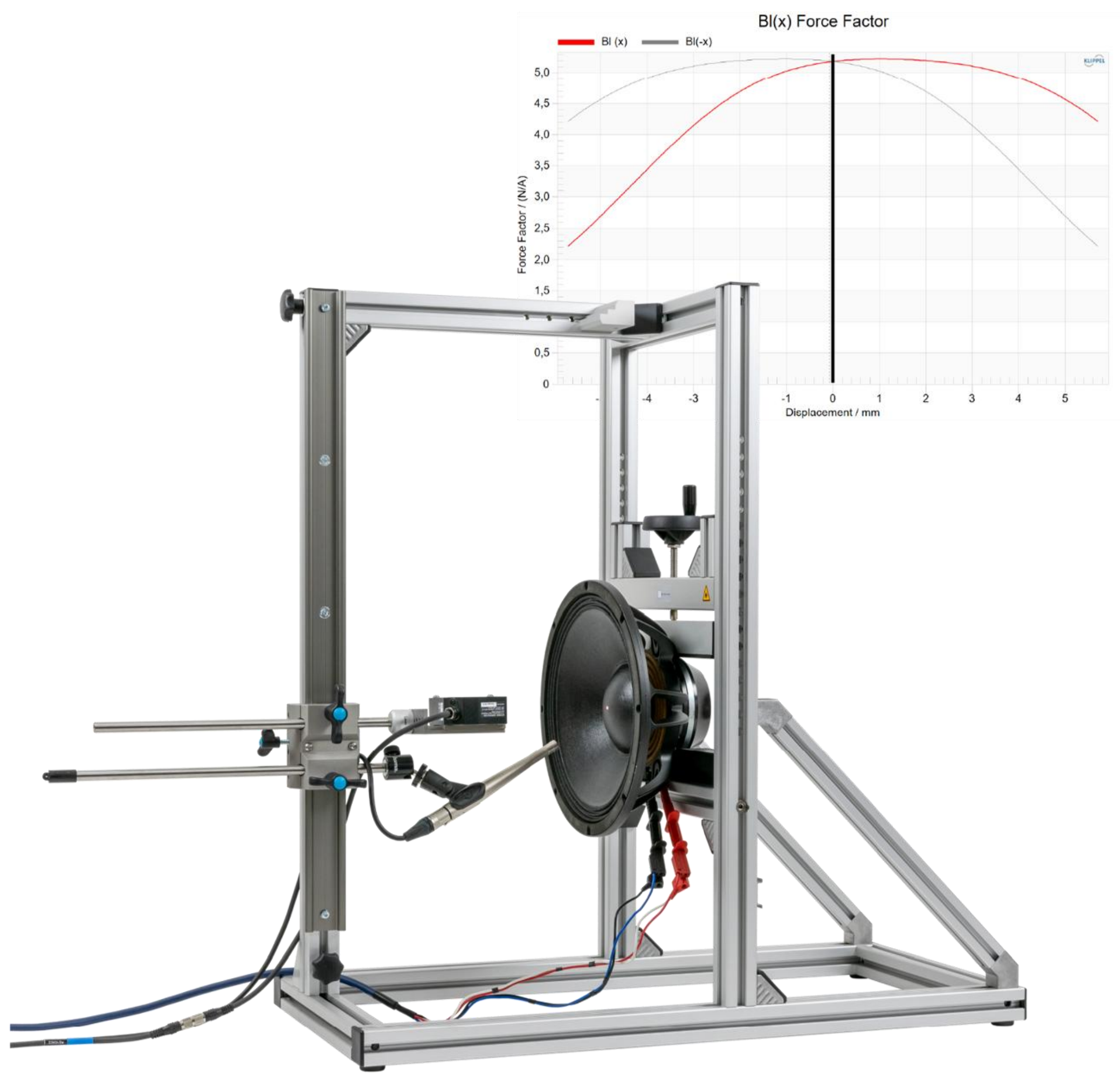
Overview

1. **Motivation & Objectives**
2. **Validation Process and Results**
   a. Validation Methodology
   b. Results
3. **Interpretation**
   a. Identifying root causes of distortion
   b. Implementing practical remedies
4. **Summary**

Motivation

- Finite Element Analysis (FEA) has become an integral part in transducer design, used for the design of all relevant components:
    - Motor Design
    - Mechanical Design (Suspension)
    - Acoustical Design (Ports)
- Validation of simulation results remains challenging:
    - What and how to compare? What is important?
    - Which tools are required?
- How to interprete simulation results?
- How to apply FEA and lumped-parameter simulations for improving the transducer?





Focus on the transducer motor: Force factor Bl(x) and self-inductance

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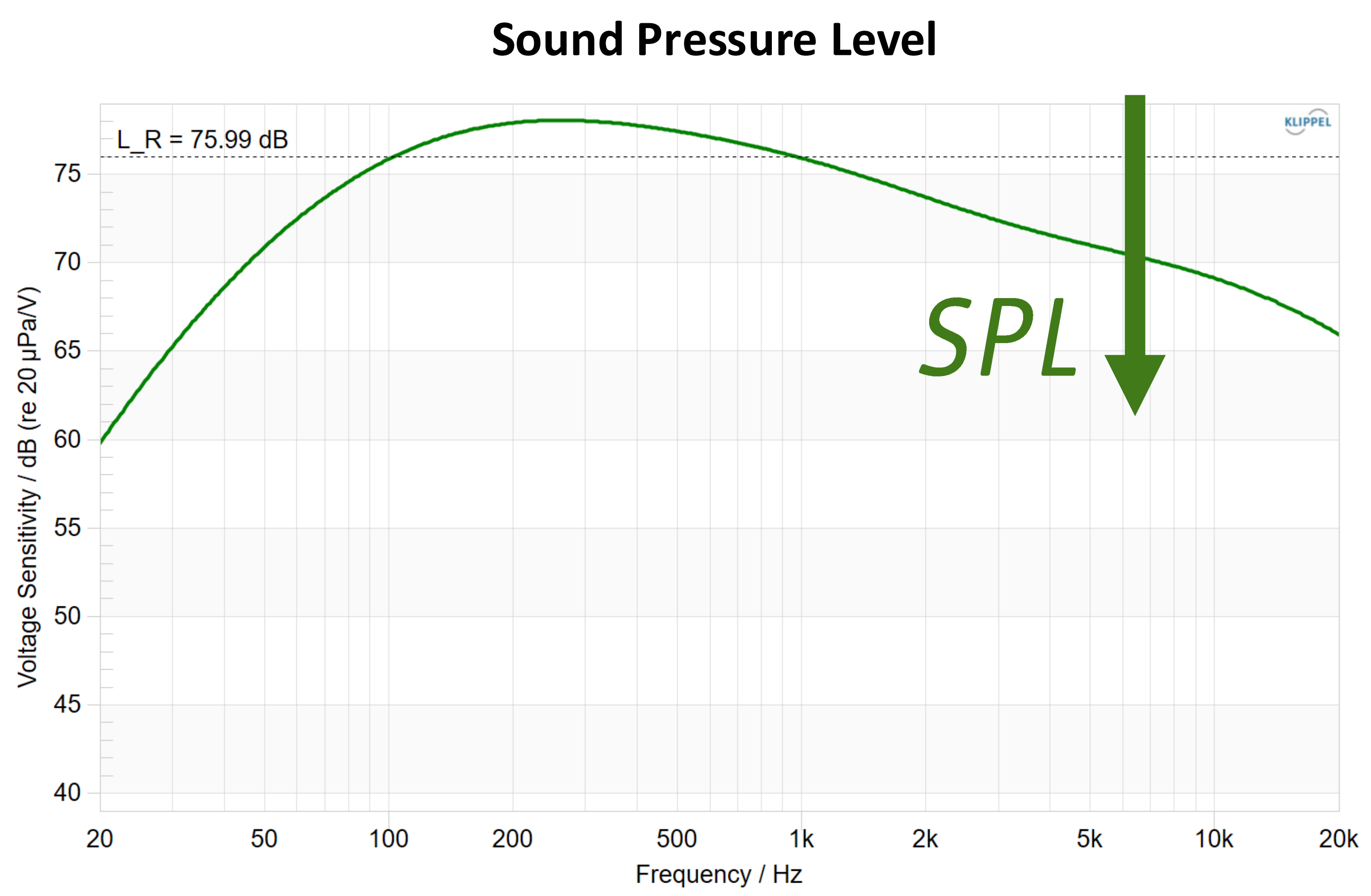
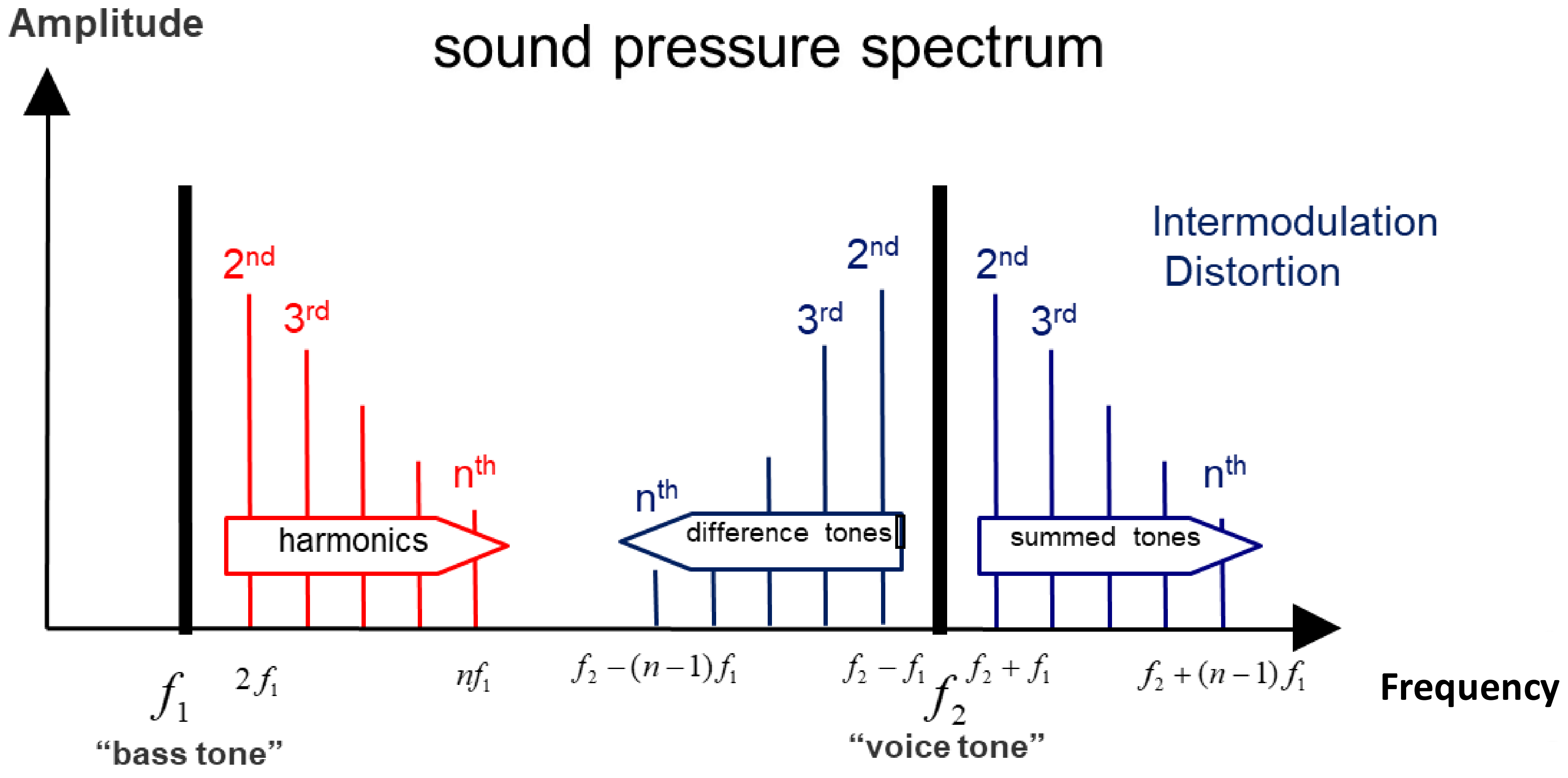
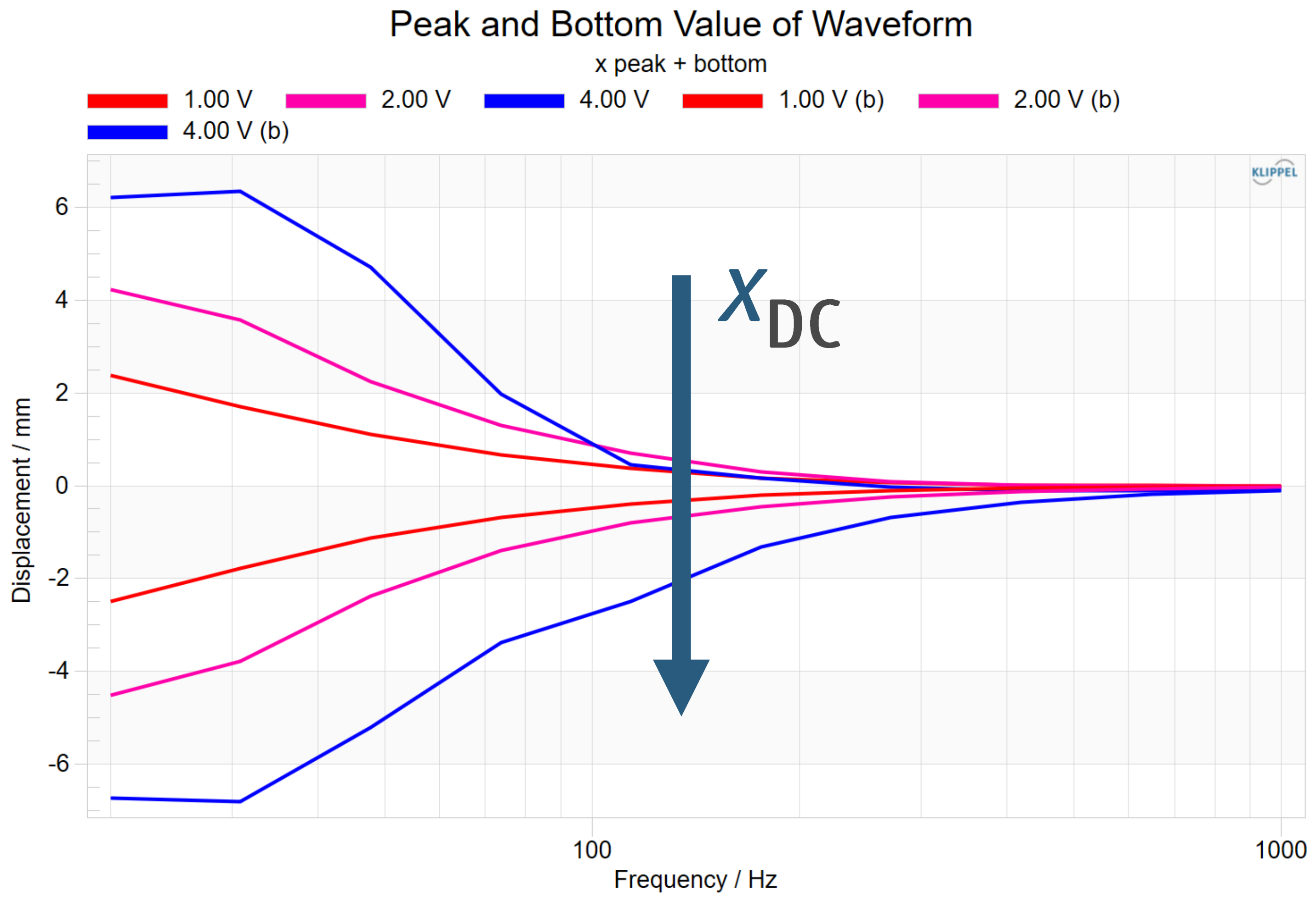
Motivation

Why is simulation and measurement required?

- Linear and nonlinear behavior must be understood across a wide frequency range (DC to multiple kHz)
- Linear mechanisms determine frequency response, sensitivity, efficiency
- Nonlinear behavior in the transducer motor
  - decreases the voltage sensitivity and efficiency,
  - creates nonlinear distortion (harmonics, intermodulation) that degrades the audio quality, and
  - cause DC displacement that decreases voice coil stability







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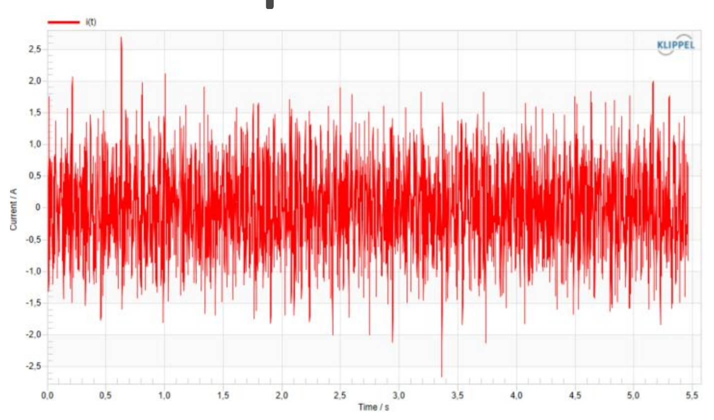
Validation Process

Step 1: Lumped Parameters

measured signals:
- voltage
- current
- displacement



Full dynamic measurement (KLIPPEL FLSI)

↓

Parameter Identification

↓

Lumped Parameters (measured)

fs, Qts, Bl(x), Kms(x), …

Comparison ⟷

FEA (COMSOL)

↓

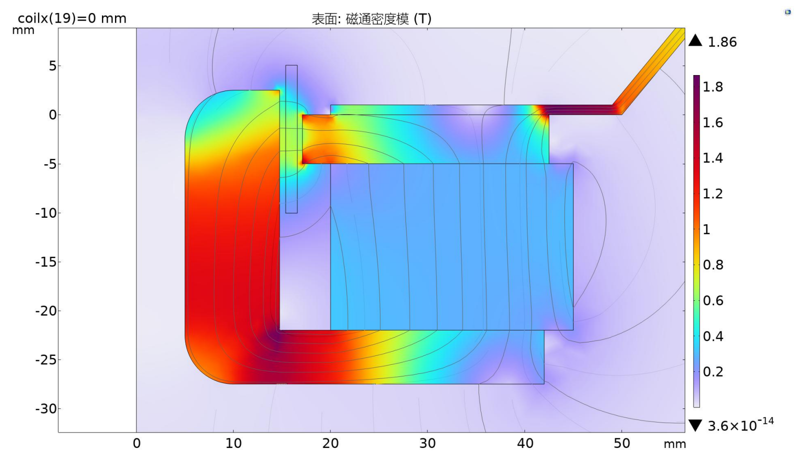
Parameter Computation

↓

Lumped Parameters (simulated)

fs, Qts, Bl(x), Kms(x), …

simulated states:
- B-field B(f,r)
- Current Density



STEP 1: Parameters

STEP 2: Symptoms

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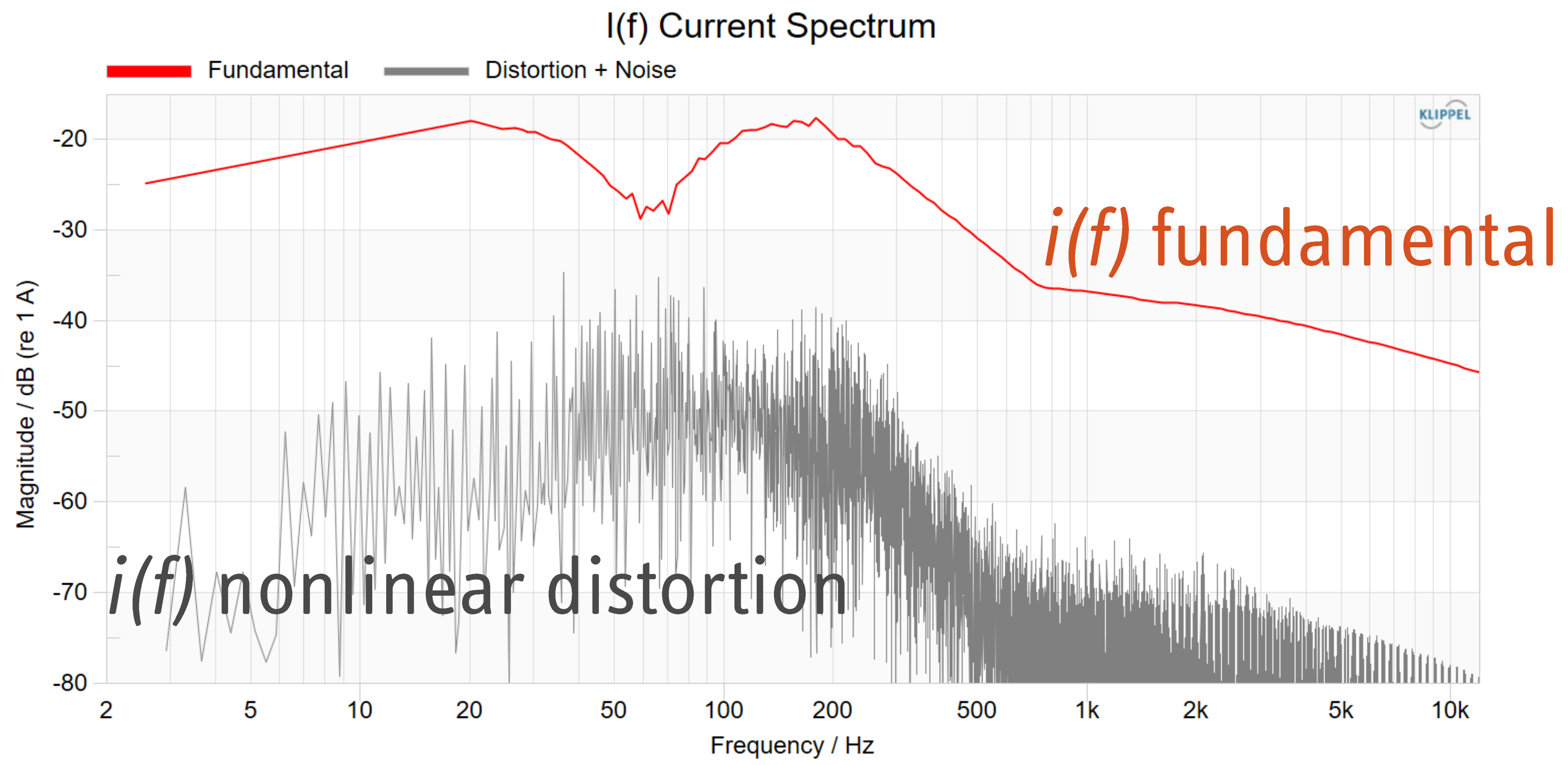
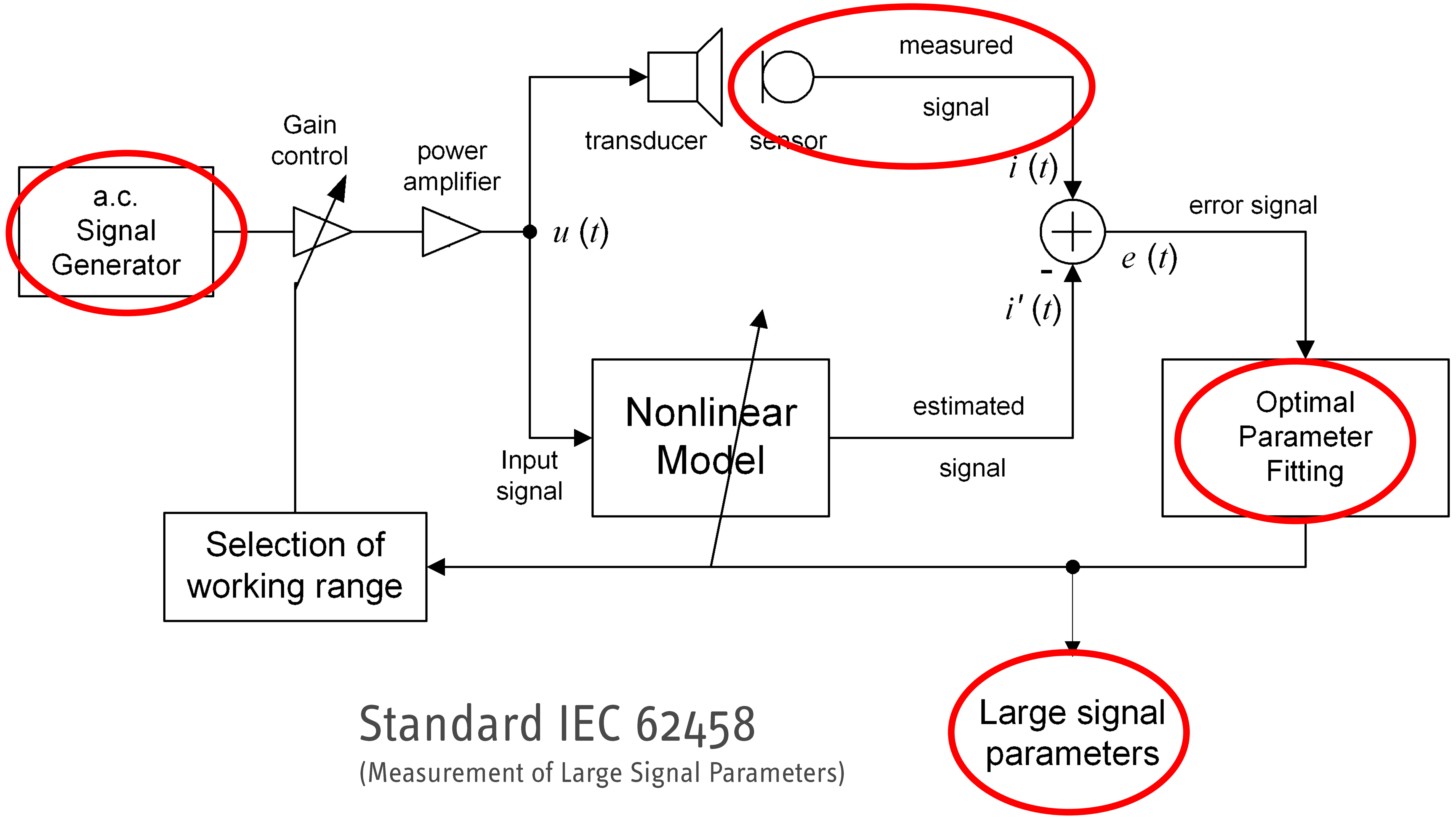
Validation Process: Lumped Parameters

Full Dynamic Measurement

- **Transducer is excited by a multi-tone signal of large amplitude**
- **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 lumped model parameters

Standard IEC 62458
(Measurement of Large Signal Parameters)

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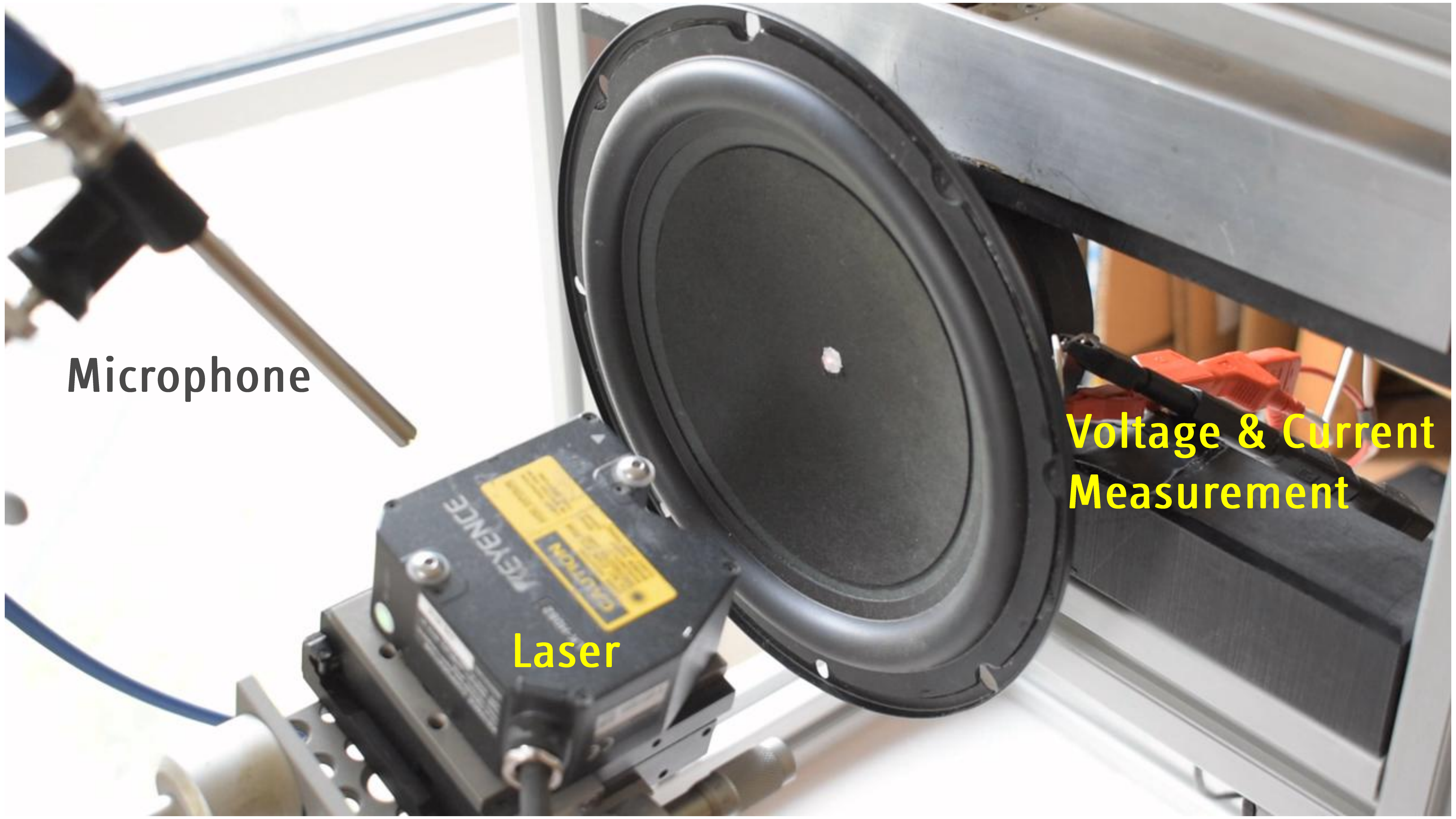
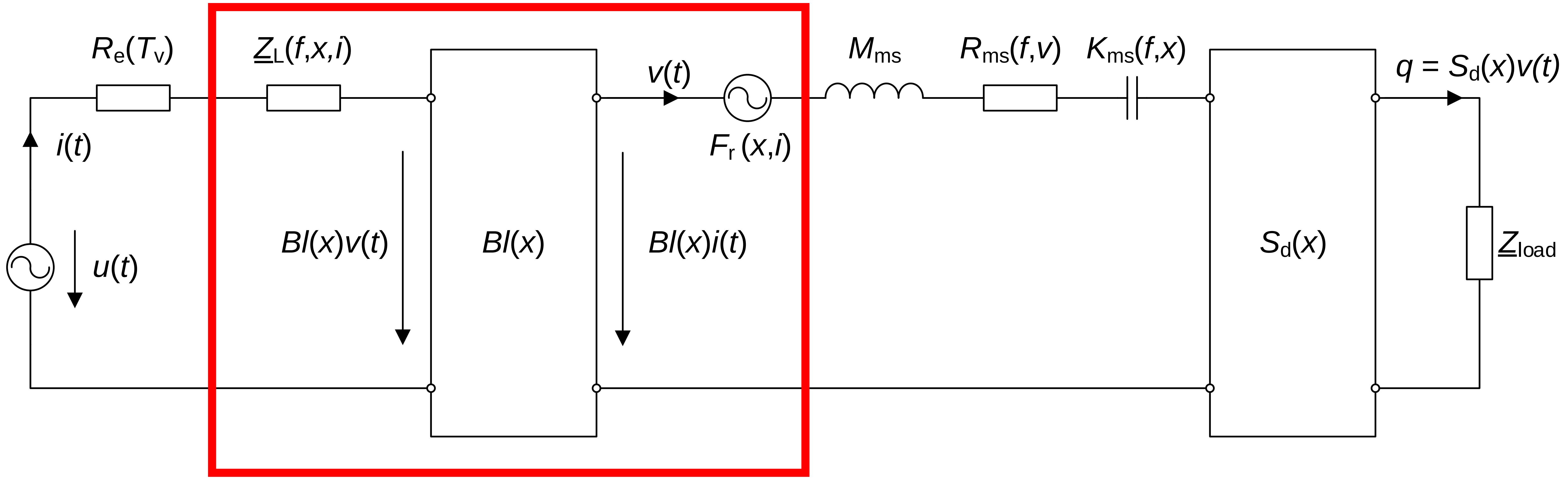
Validation Process: Lumped Parameters

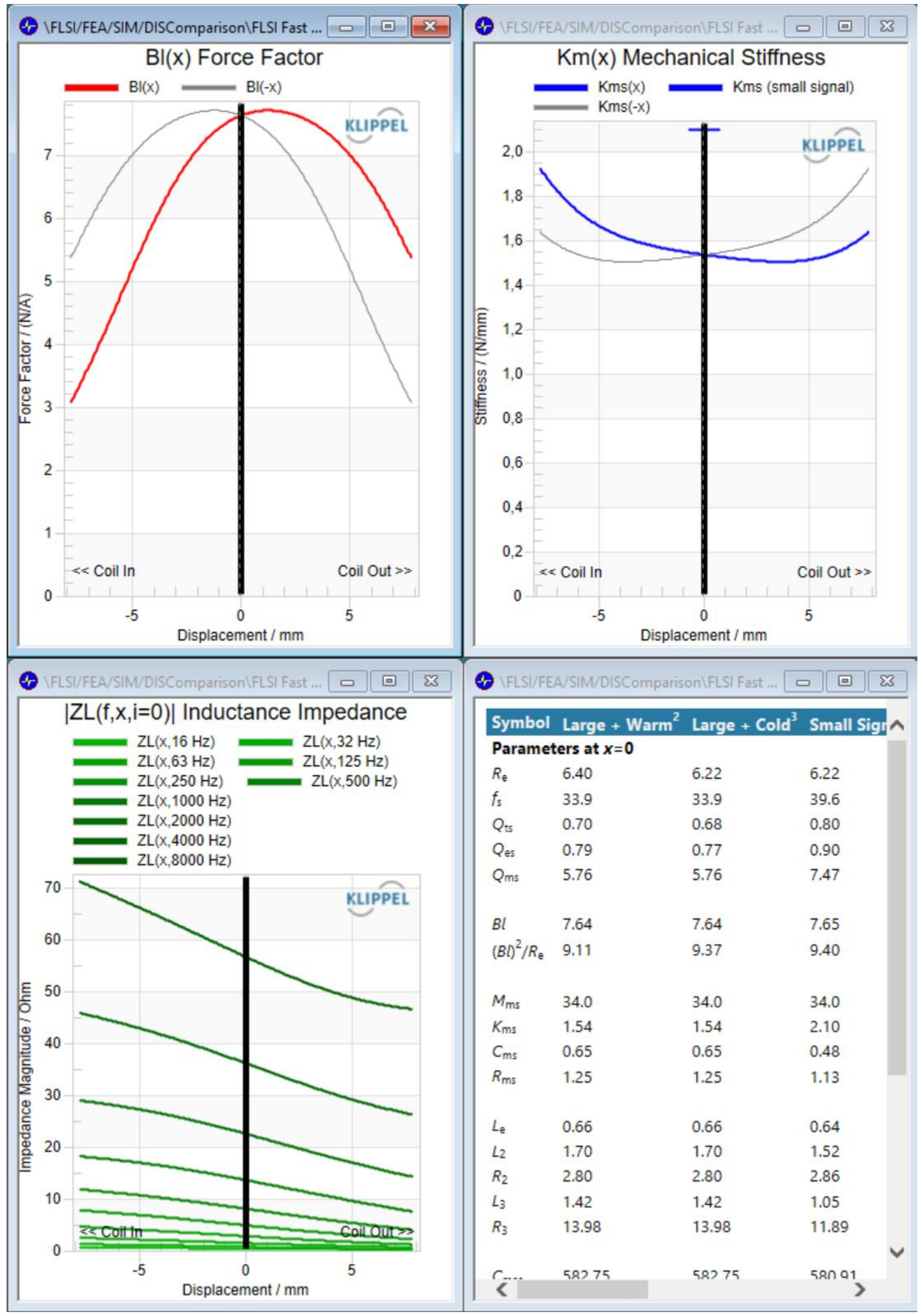
Measurement - Video



Validation Process: Lumped Parameters

Measurement - Results





Symbol	Large + Warm[2]	Large + Cold[3]	Small Sign
Parameters at $x=0$			
R_e	6.40	6.22	6.22
f_s	33.9	33.9	39.6
Q_{ts}	0.70	0.68	0.80
Q_{es}	0.79	0.77	0.90
Q_{ms}	5.76	5.76	7.47
Bl	7.64	7.64	7.65
$(Bl)^2/R_e$	9.11	9.37	9.40
M_{ms}	34.0	34.0	34.0
K_{ms}	1.54	1.54	2.10
C_{ms}	0.65	0.65	0.48
R_{ms}	1.25	1.25	1.13
L_e	0.66	0.66	0.64
L_2	1.70	1.70	1.52
R_2	2.80	2.80	2.86
L_3	1.42	1.42	1.05
R_3	13.98	13.98	11.89
[illegible]	582.75	582.75	580.91

- Measurement result: linear and nonlinear lumped parameters
- Focus is on the transducer motor, described by
  - Force Factor Bl(x)
  - Self-inductance $Z_L(x)$
  - Reluctance force $F_r(x)$

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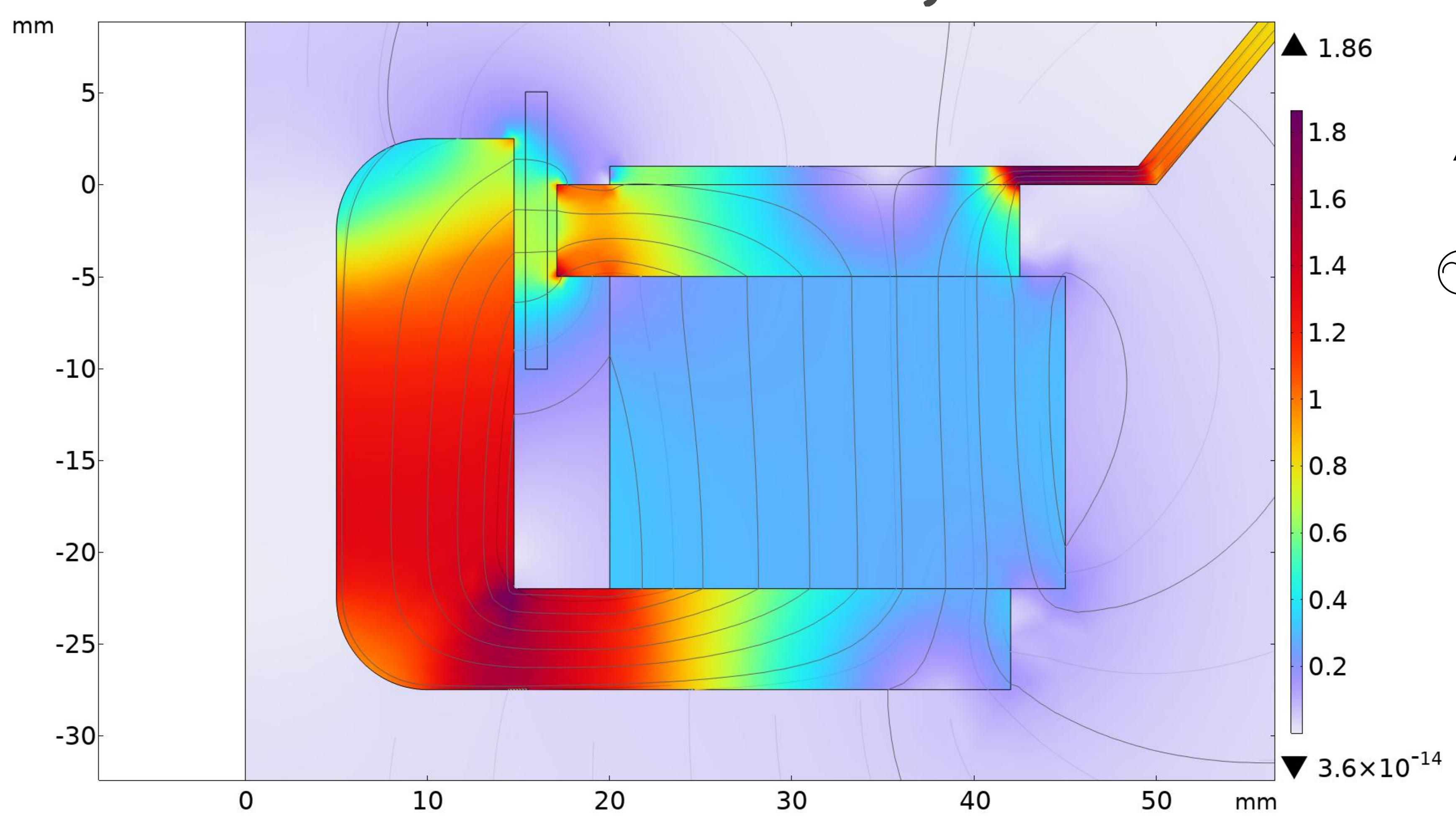
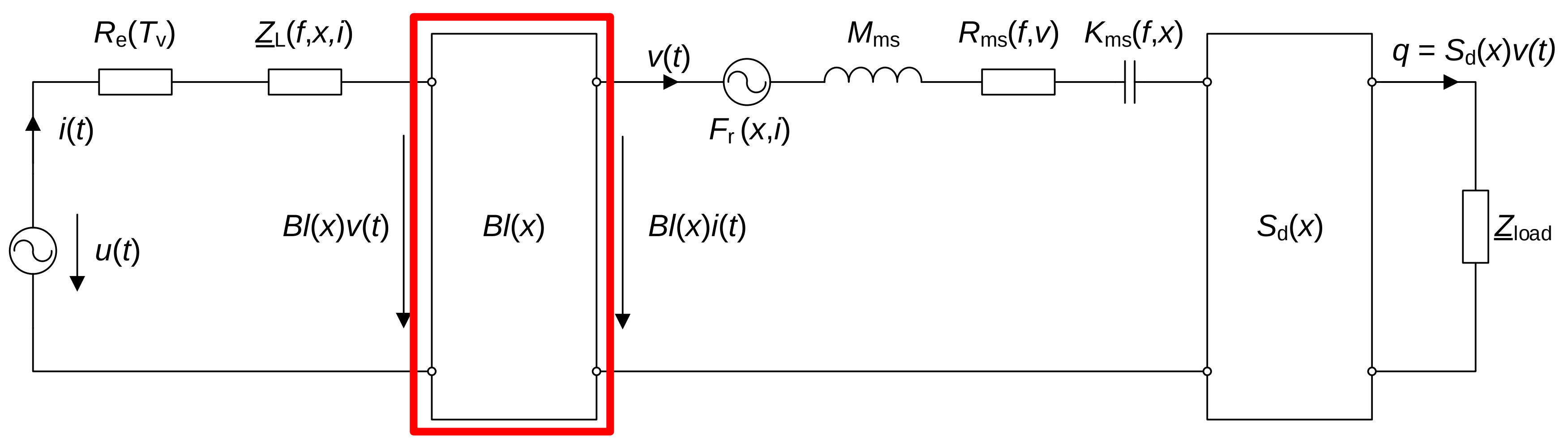
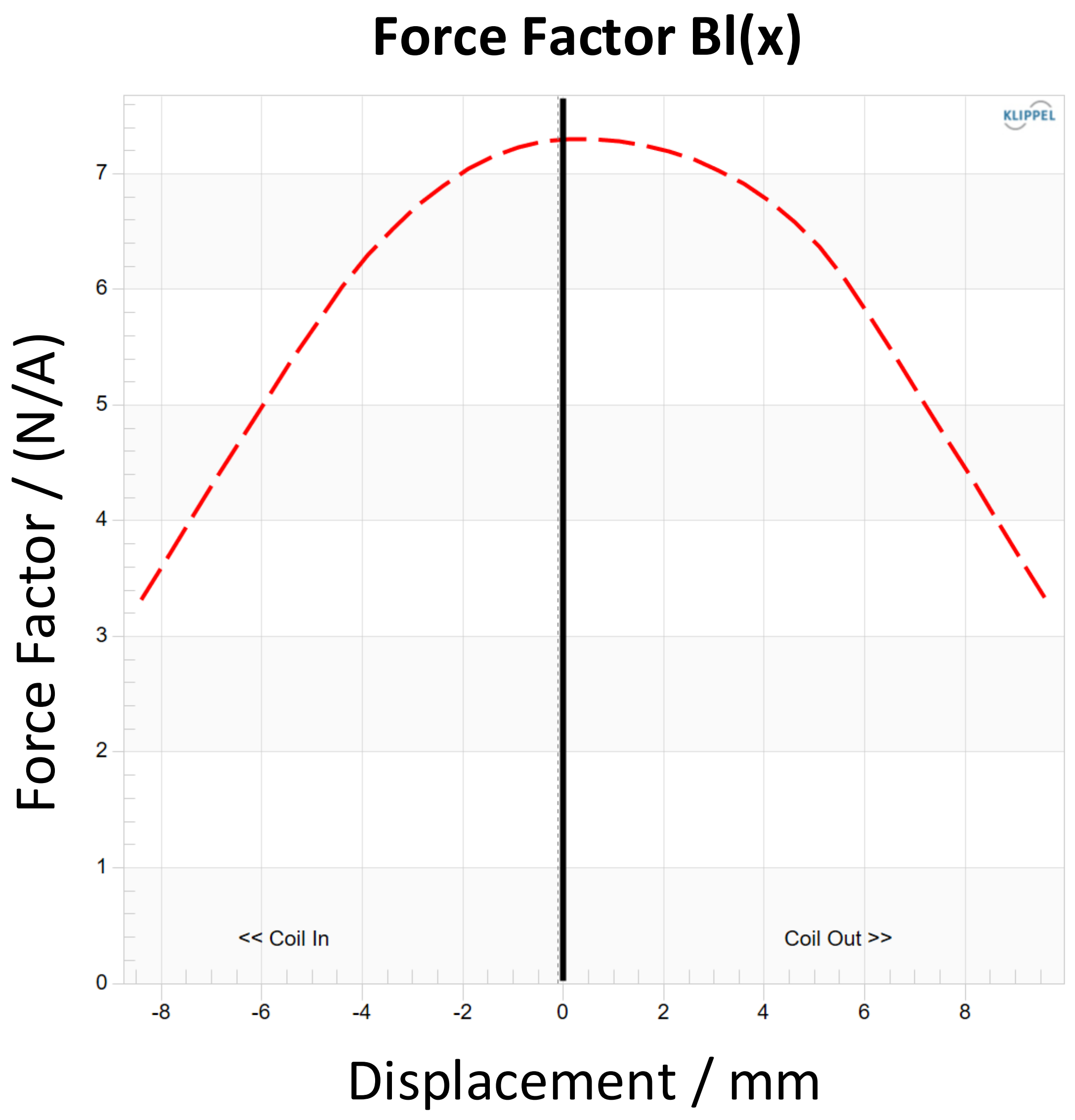
Validation Process: Lumped Parameters

Point-by-point FEA (Force Factor)

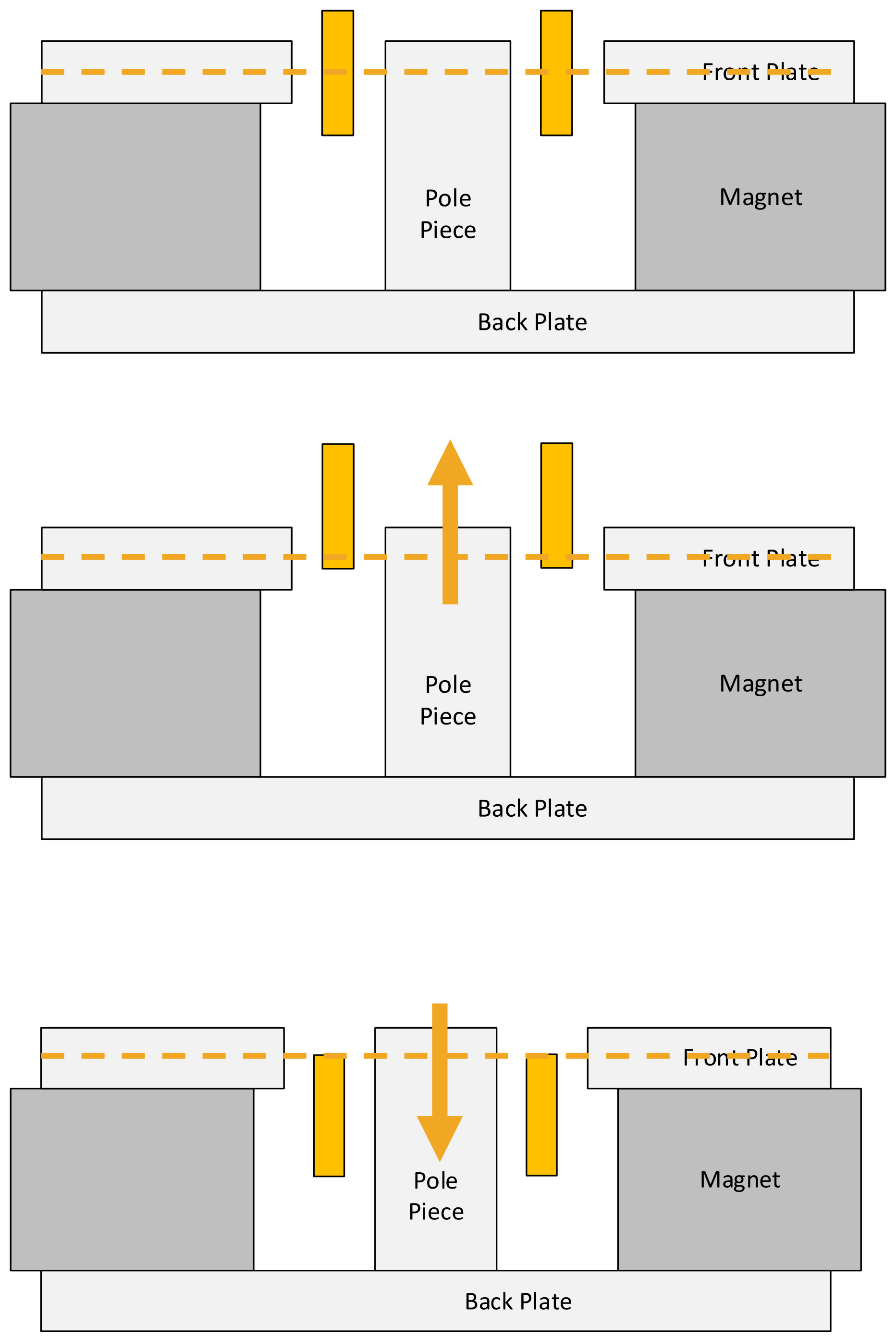
Simulated Stationary B-field







Voice Coil is shifted to multiple positions x_k



$$Bl(x_k) = \frac{1}{h}\int_{x_k-h/2}^{x_k+h/2} B_r(z, x_k)\cdot l\,\mathrm{d}z$$

B_r - static B-field by caused by magnet
l - wire length
h - voice coil height

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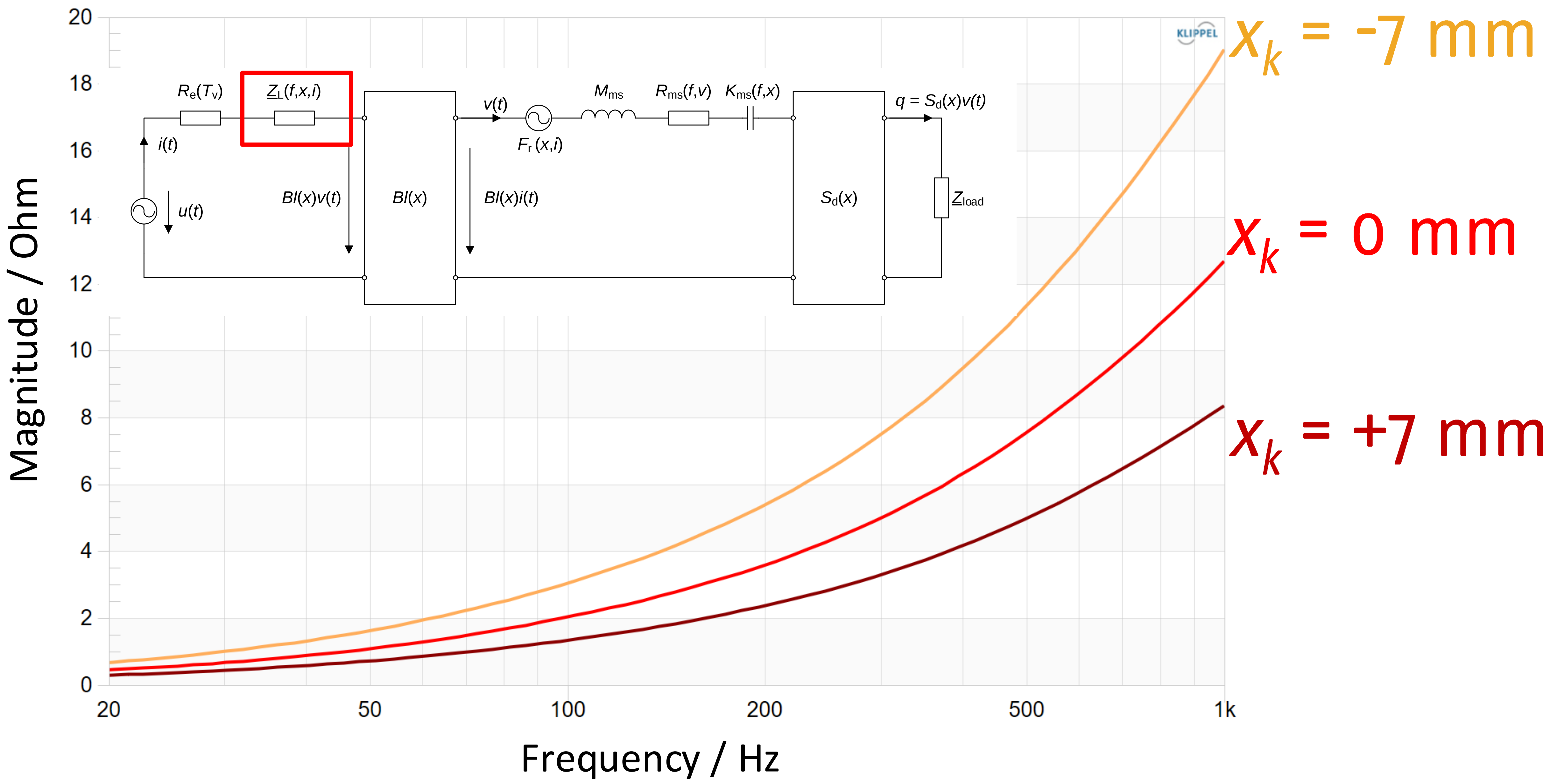
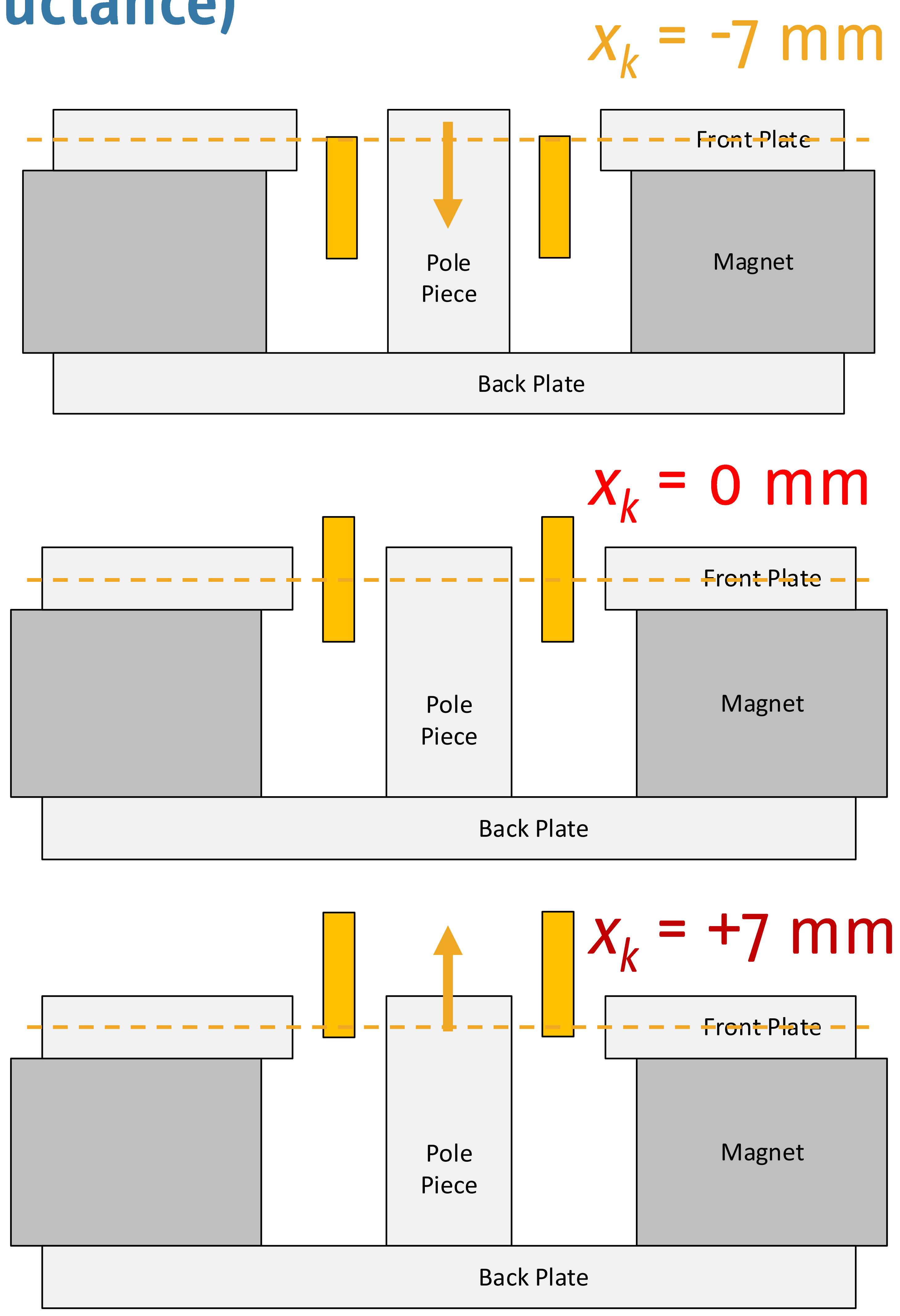
Validation Process: Lumped Parameters

Point-by-point FEA (Self-inductance)

- The voice coil is shifted to different positions x_k
- At each position, a small AC voltage is applied
- Set of small signal electrical impedances $Z_L(f,x)$ of the blocked voice coil is computed

Impedance of Lossy Inductance





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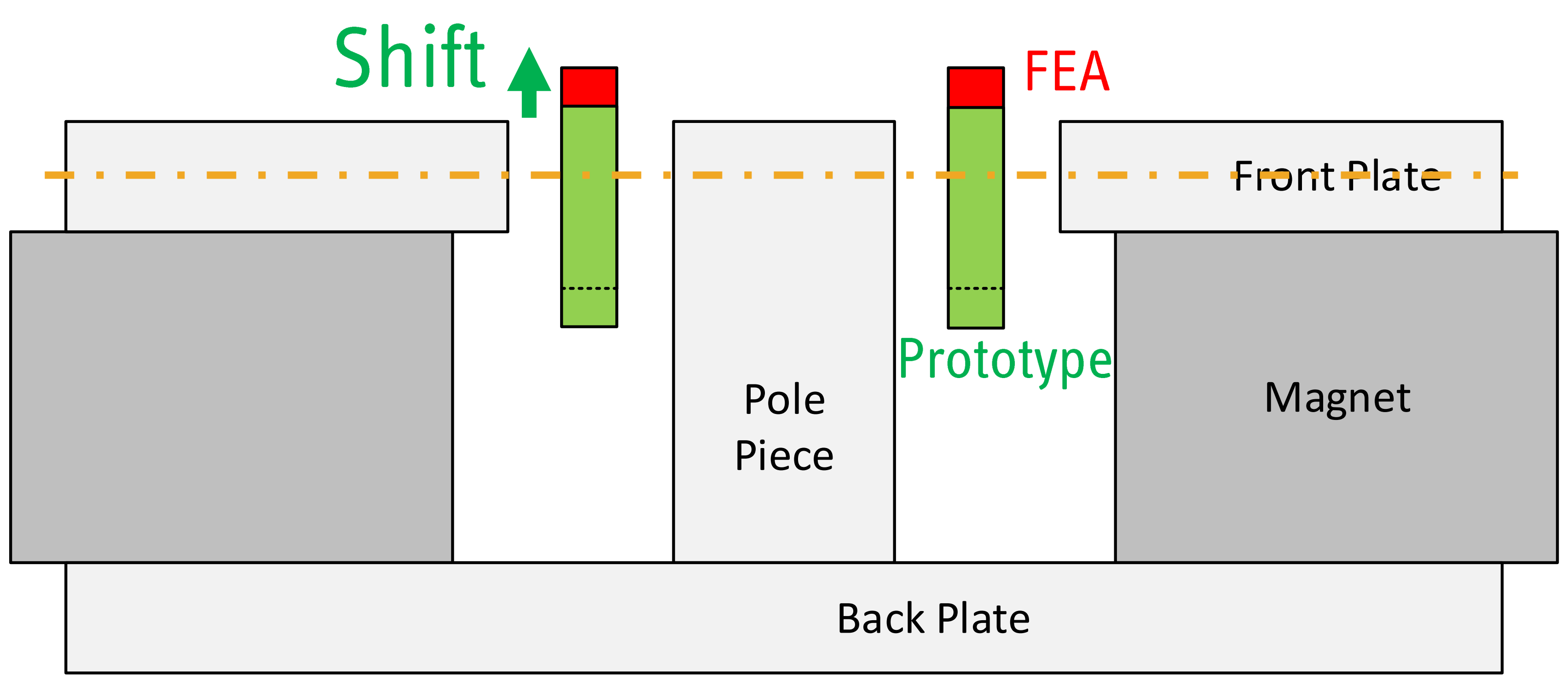
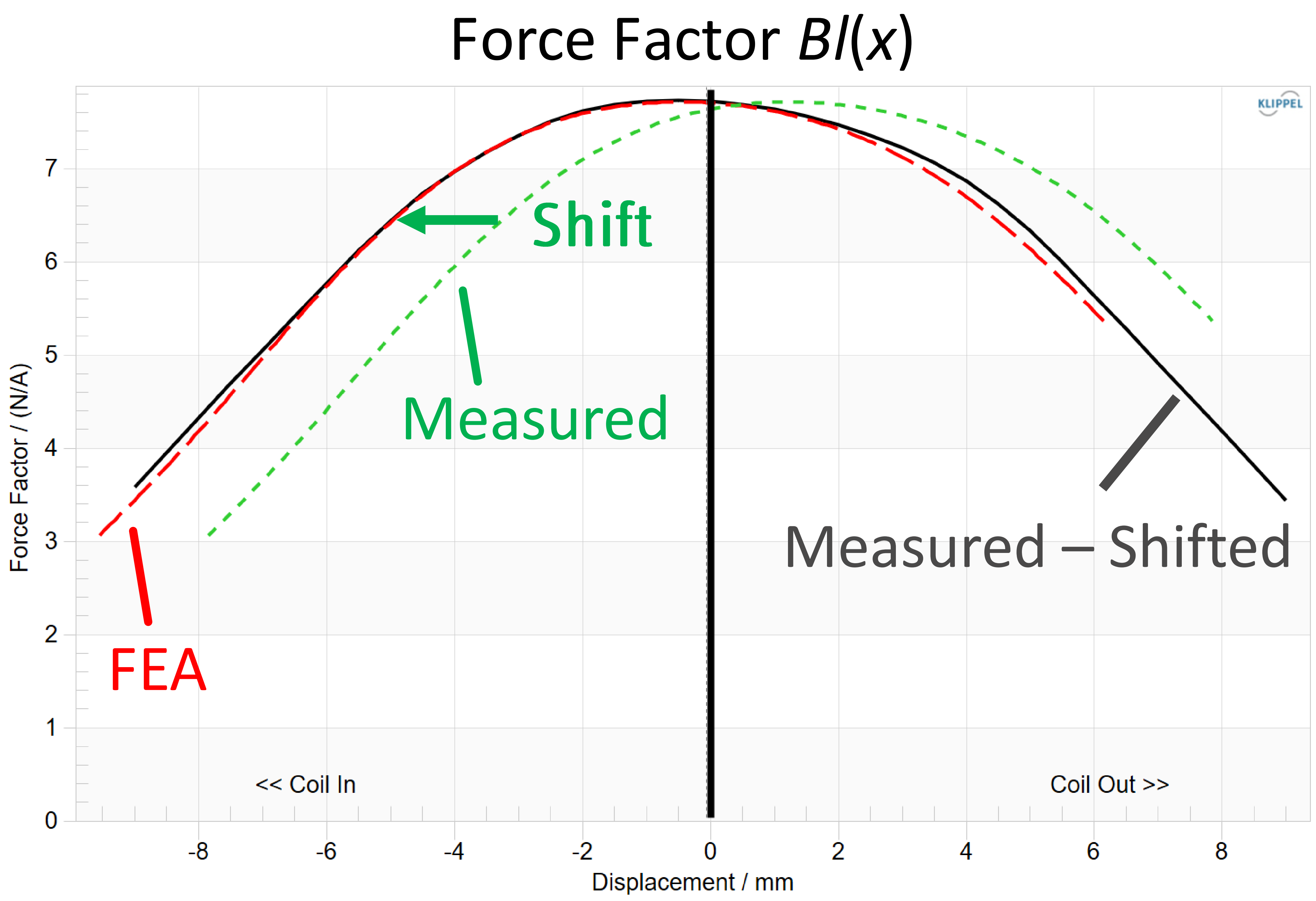
Validation Results: Parameters

Force Factor

- prototype's voice coil position has an offset due to manual assembly
- voice coil is shifted before comparison
- **after shift, FEA and measurement agree very well – error is below 4 %**





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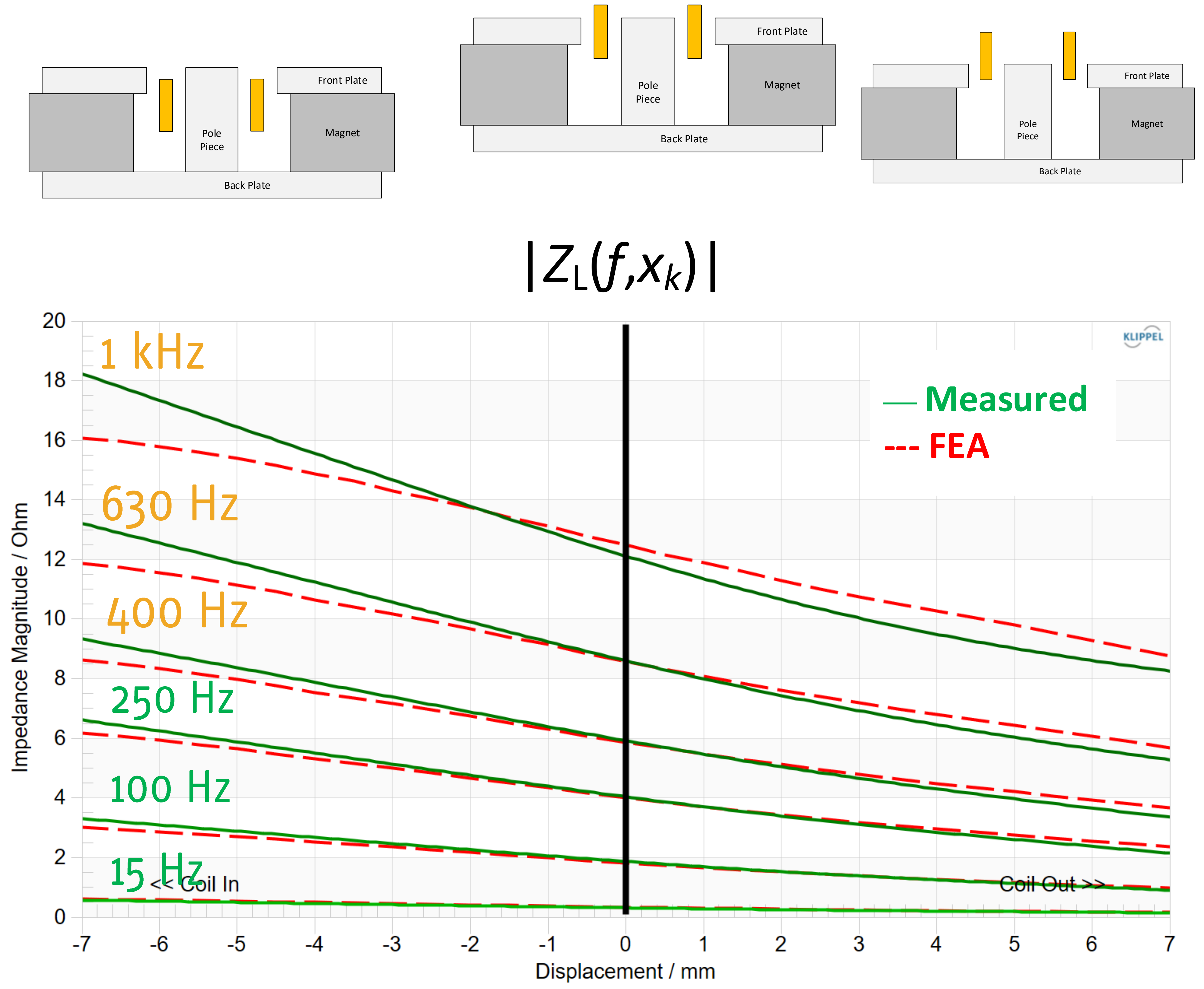
Validation Results: Parameters

Self-inductance

- very good agreement at rest position x = 0 mm
- very good agreement at low frequencies
- good agreement at x >> 0 mm, when the coil moves out of the gap
- fair agreement at x << 0 mm, when the coil moves toward the back plate



Possible causes for deviations:

- systematic discrepancies between the parameter extraction methodologies: full dynamic measurement vs point-by-point FEA (large-signal vs. small-signal)
- discrepancies in simulated idealized and real material properties
- assembly tolerances

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Validation Process

Step 2: Symptoms

measured signals:
- voltage
- current
- displacement

Full dynamic measurement (KLIPPEL FLSI)

Parameter Identification

Lumped Parameters (measured)

fs, Qts, Bl(x), Kms(x), ...

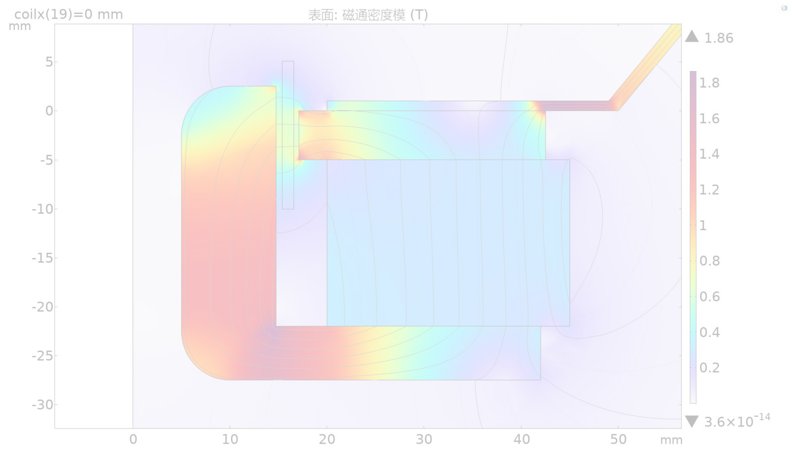
Comparison

FEA (COMSOL)

Parameter Computation

Lumped Parameters (simulated)

simulated states:
- B-field B(f,r)
- Current Density



fs, Qts, Bl(x), Kms(x), ...

STEP 1: Parameters

STEP 2: Symptoms
- frequency responses
- <u>DC displacement</u>
- <u>harmonic distortion</u>
- intermodulation distortion

Lumped-Parameter Simulation

Comparison

Symptom Measurements

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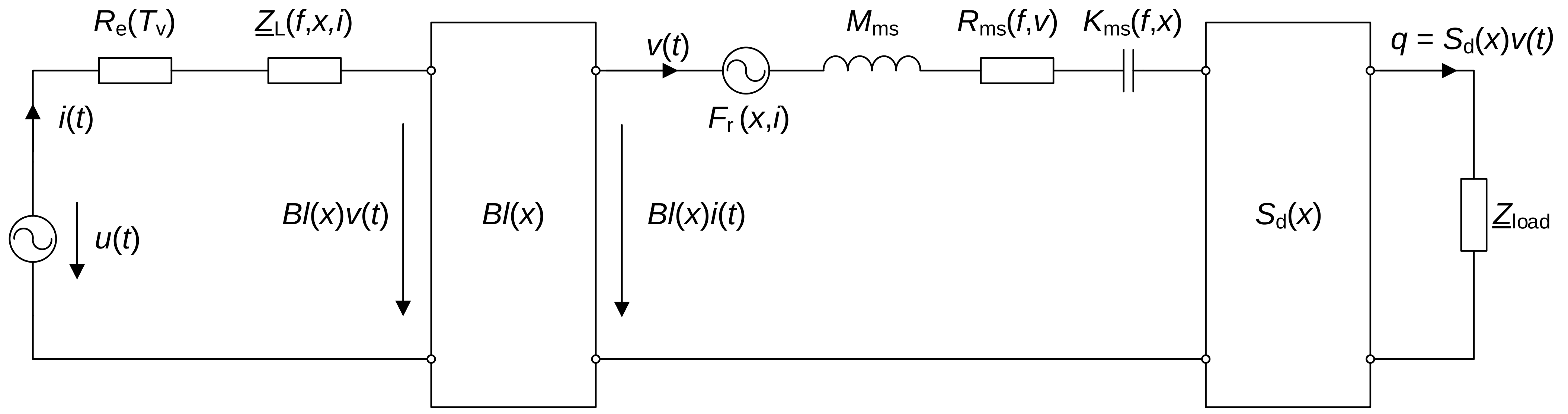
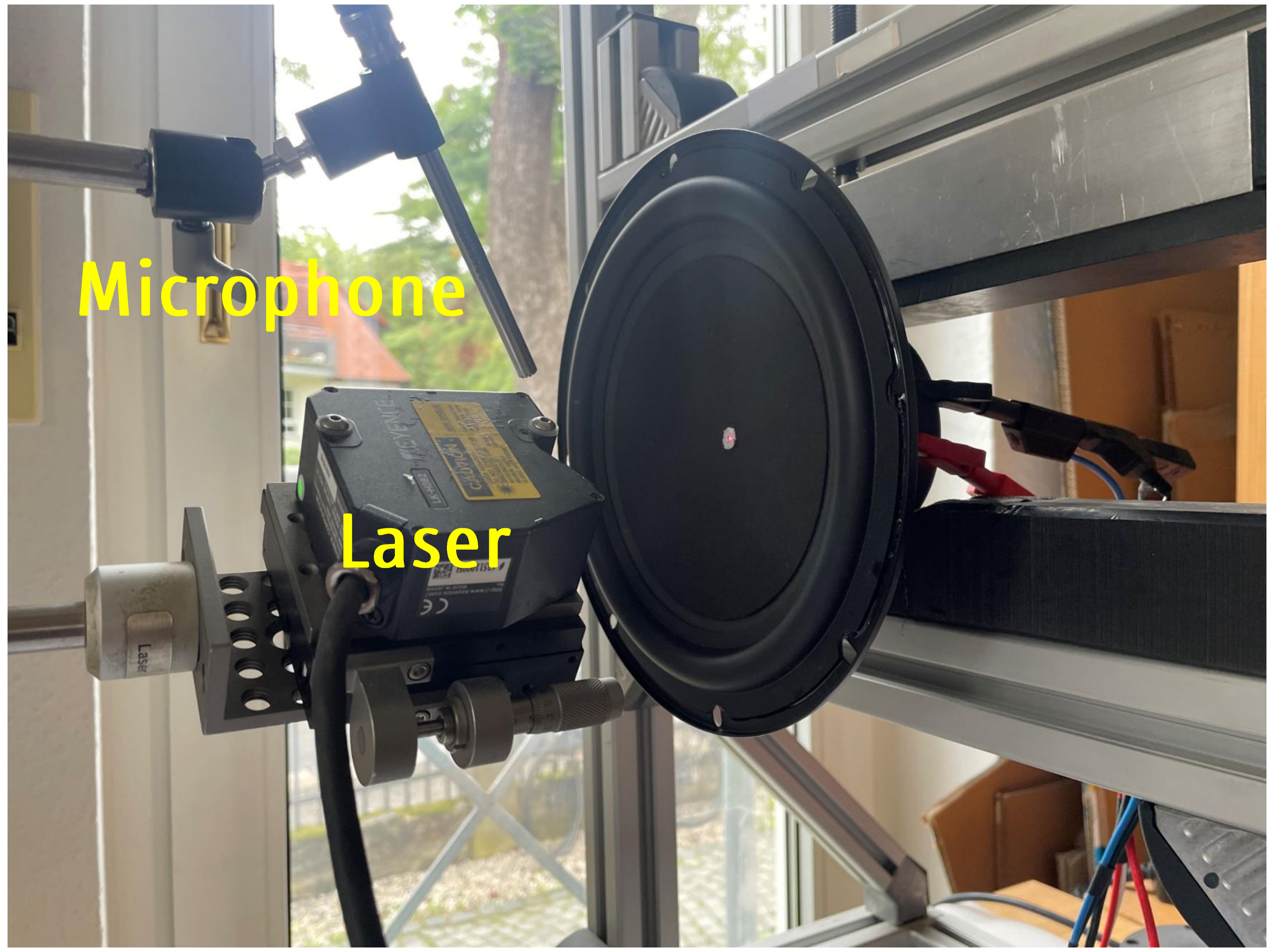
Validation Process: Symptoms

Simulation and Measurement



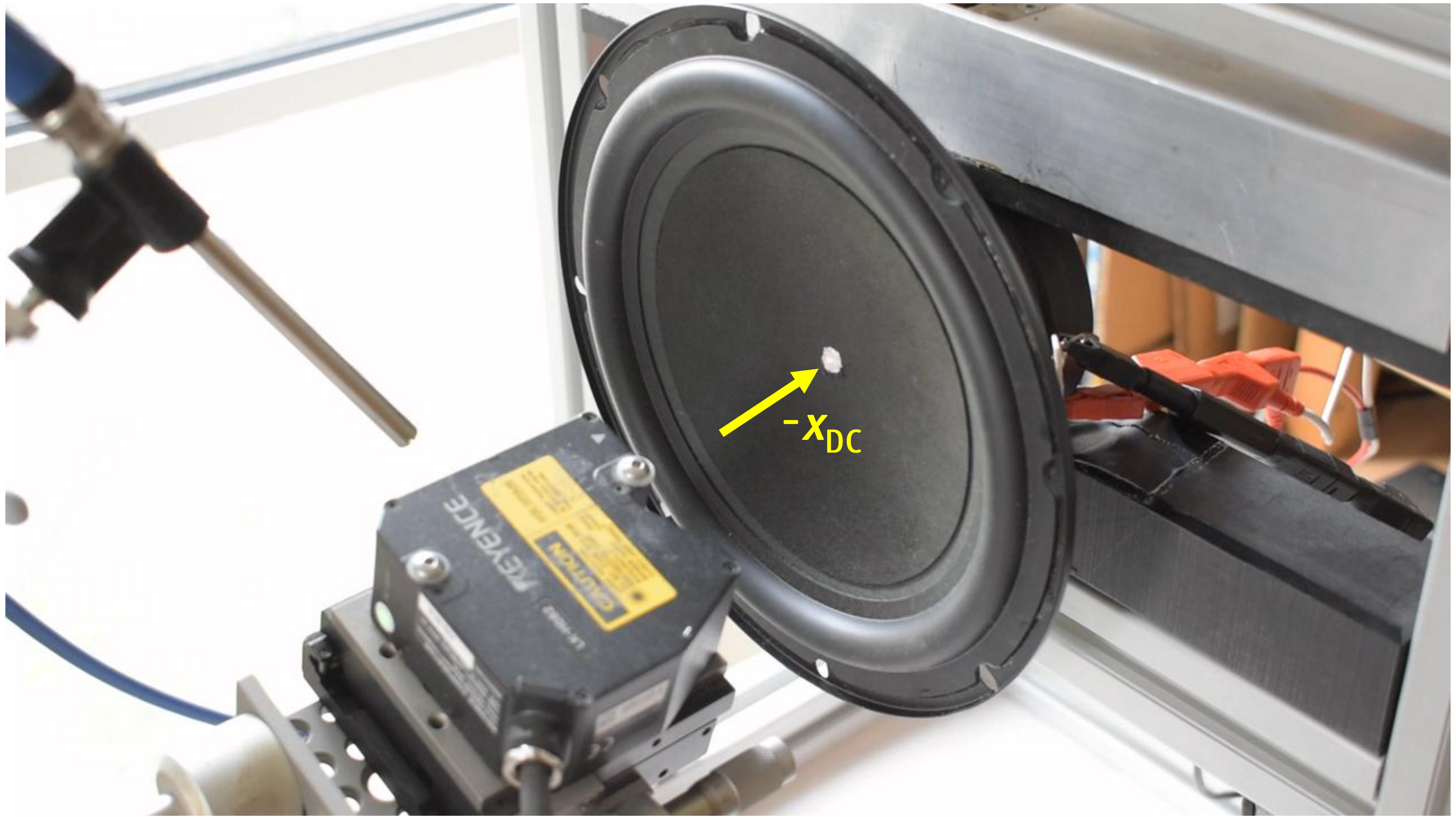


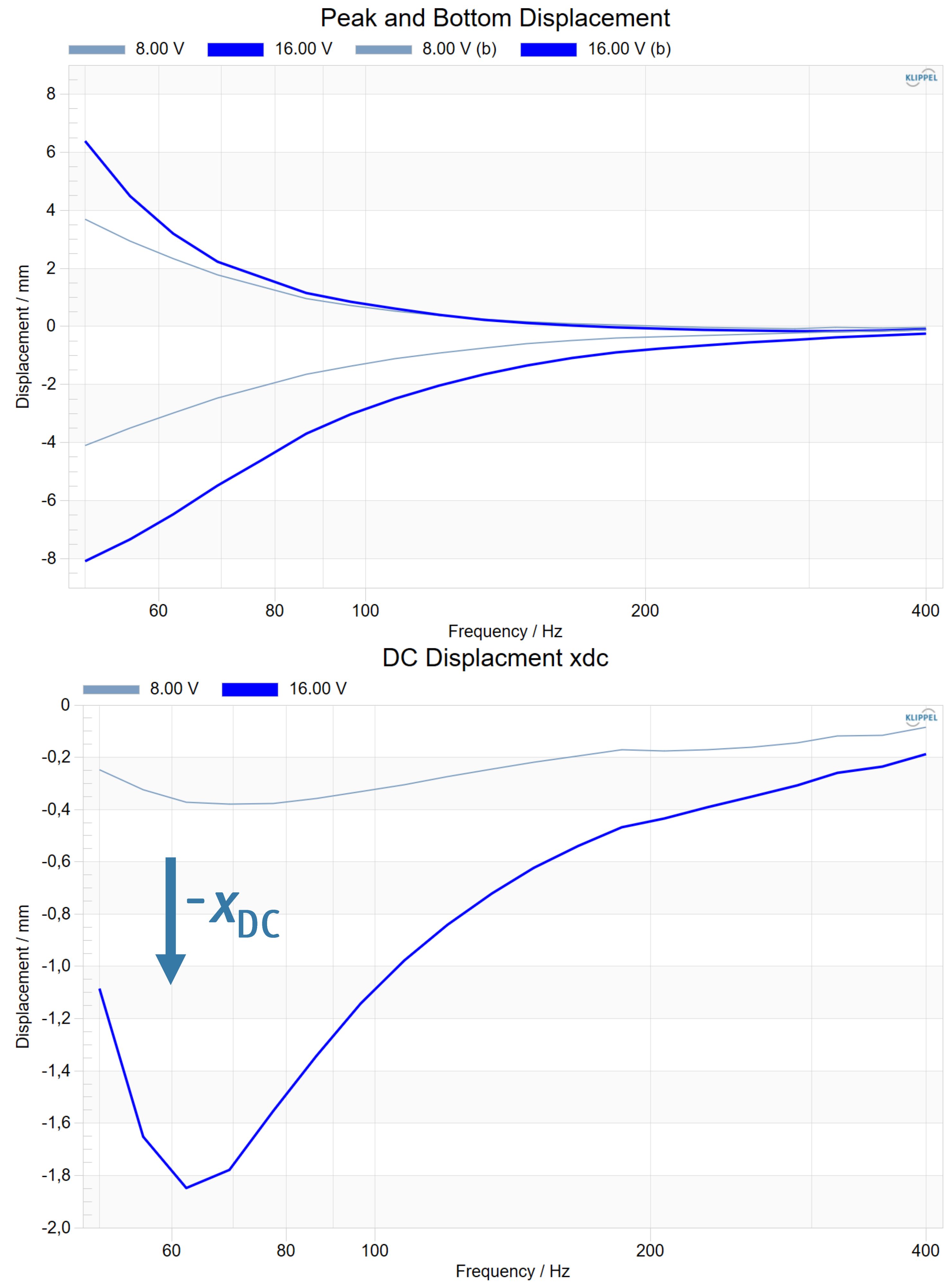
- Stepped sine stimulus: Sinusoidal excitation at different frequencies
- Measurement and simulation of sound pressure and voice coil displacement
- Evaluation of DC displacement and harmonic distortion
- Klippel SIM2 and DIS (measurement) modules were used

Validation Process: Symptoms

Measurement - Video

Measurement of DC displacement





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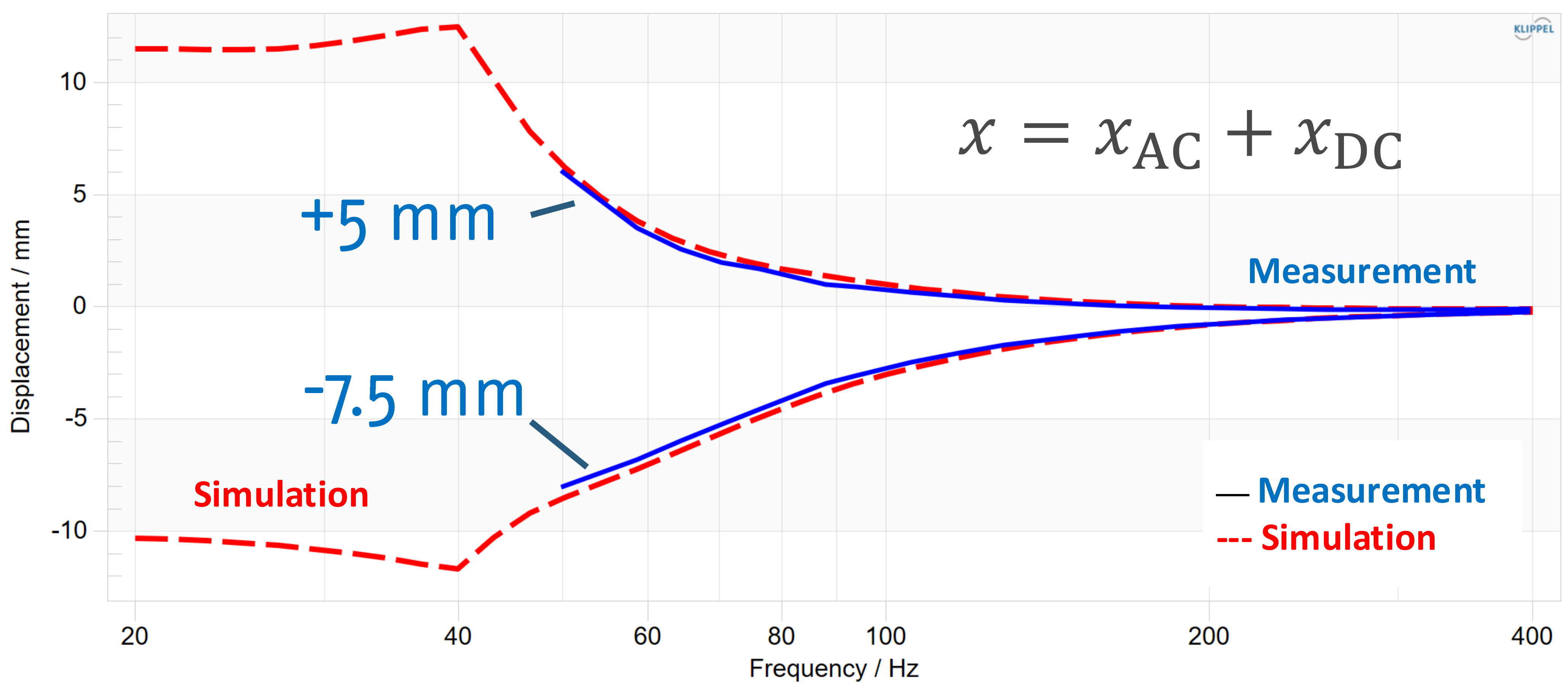
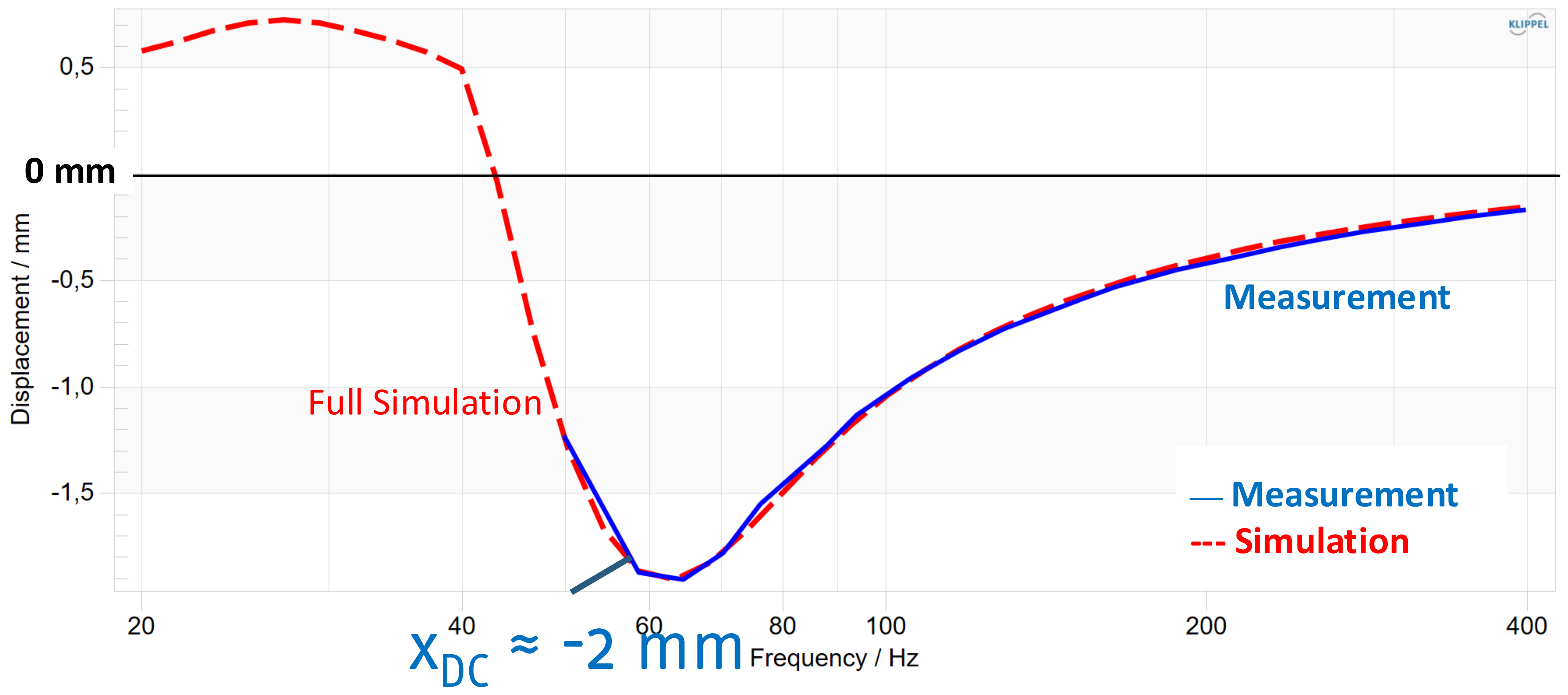
Validation Results: Symptoms

DC displacement

Peak and Bottom Displacement



DC Displacement x_{DC}



Observations:

- displacement comprises an AC and a DC component
- DC displacement is caused by nonlinear behavior
- significant DC displacement of almost -2 mm
- lower maximum voice coil movement → reduces maximum SPL
- measurement and FEA fit well

$$x_{DC}(f) = \frac{1}{T}\int_0^T x(t,f)\,\mathrm{d}t$$

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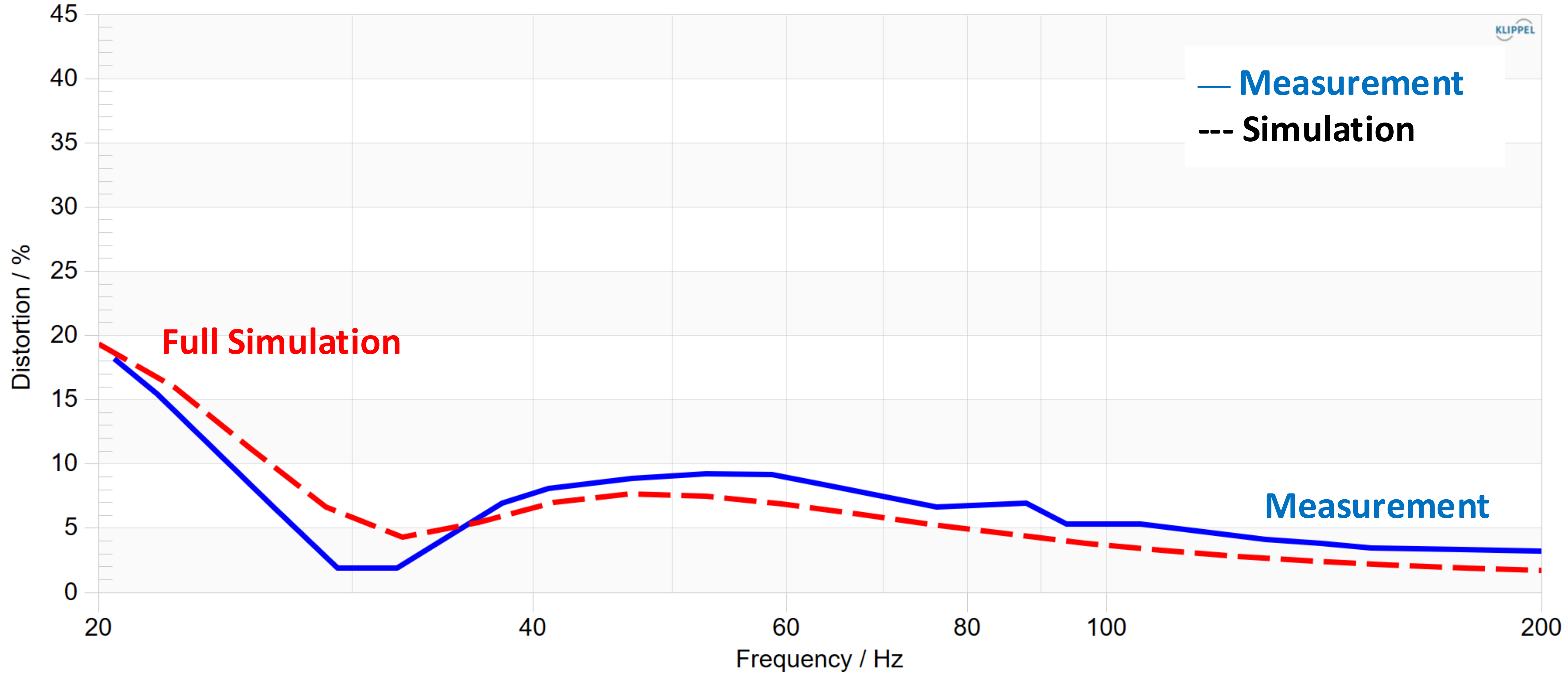
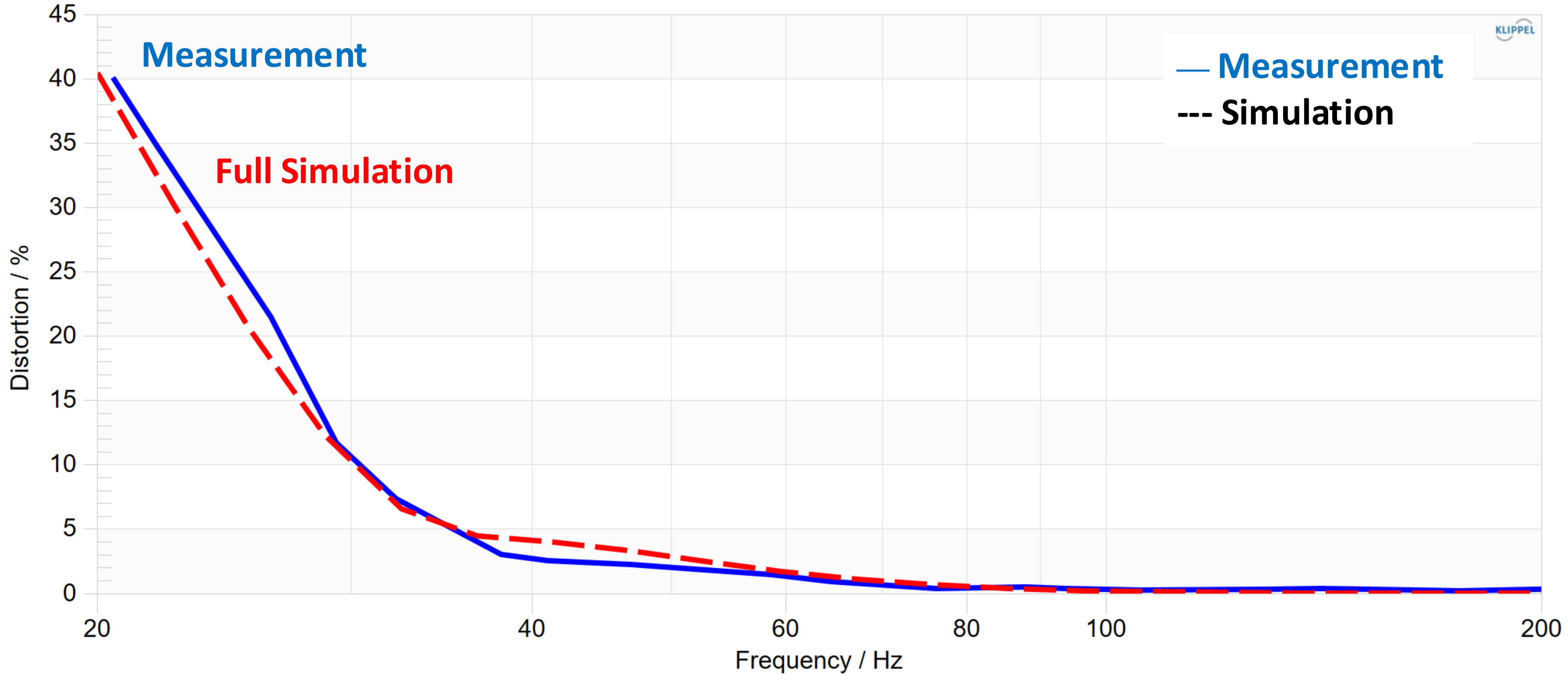
Validation Results: Symptoms

Harmonic Distortion

Relative 2nd order Harmonic Distortion



Relative 3rd order Harmonic Distortion



Observations:

- maximum 20 % 2nd order harmonic distortion
- maximum 40 % 3rd order harmonic distortion
- measurement and FEA fit well

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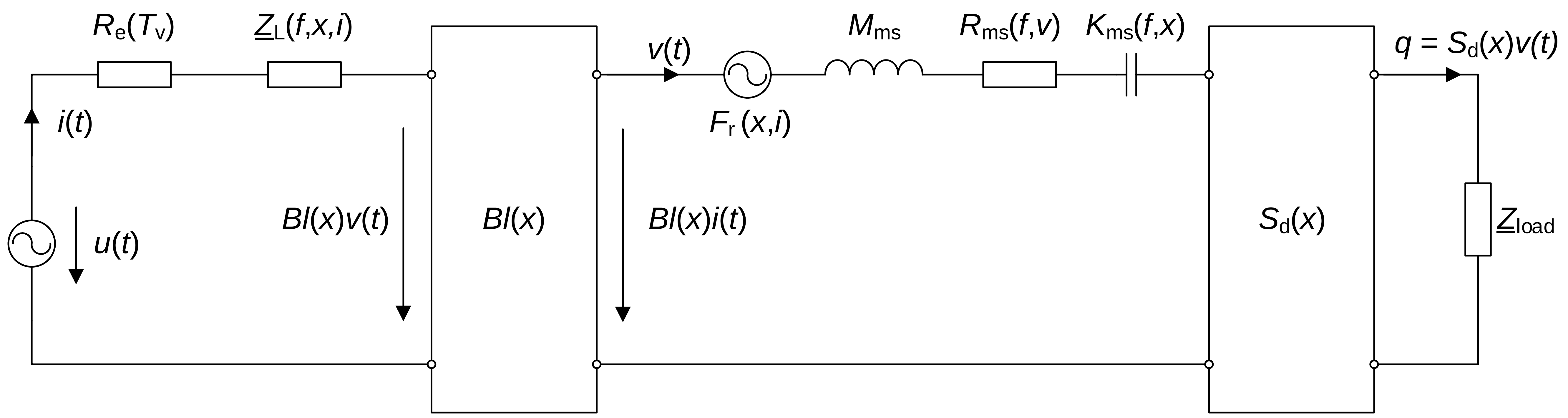
Validation Results

Lumped-Parameter Model



- **Lumped parameters obtained from measurement and FEA show <u>good agreement</u>**
- **Simulated symptoms based on lumped parameters show <u>very good agreement</u> with measurements**
- **The lumped-parameter model**
  - is <u>valid at low frequencies</u>, where the cone moves like a piston
  - gives the possibility to perform <u>fast parameter studies</u> – faster and simpler than full transient finite element analysis
  - allows <u>isolation</u> of individual nonlinearities
  - can be obtained from either full FEA or measurement

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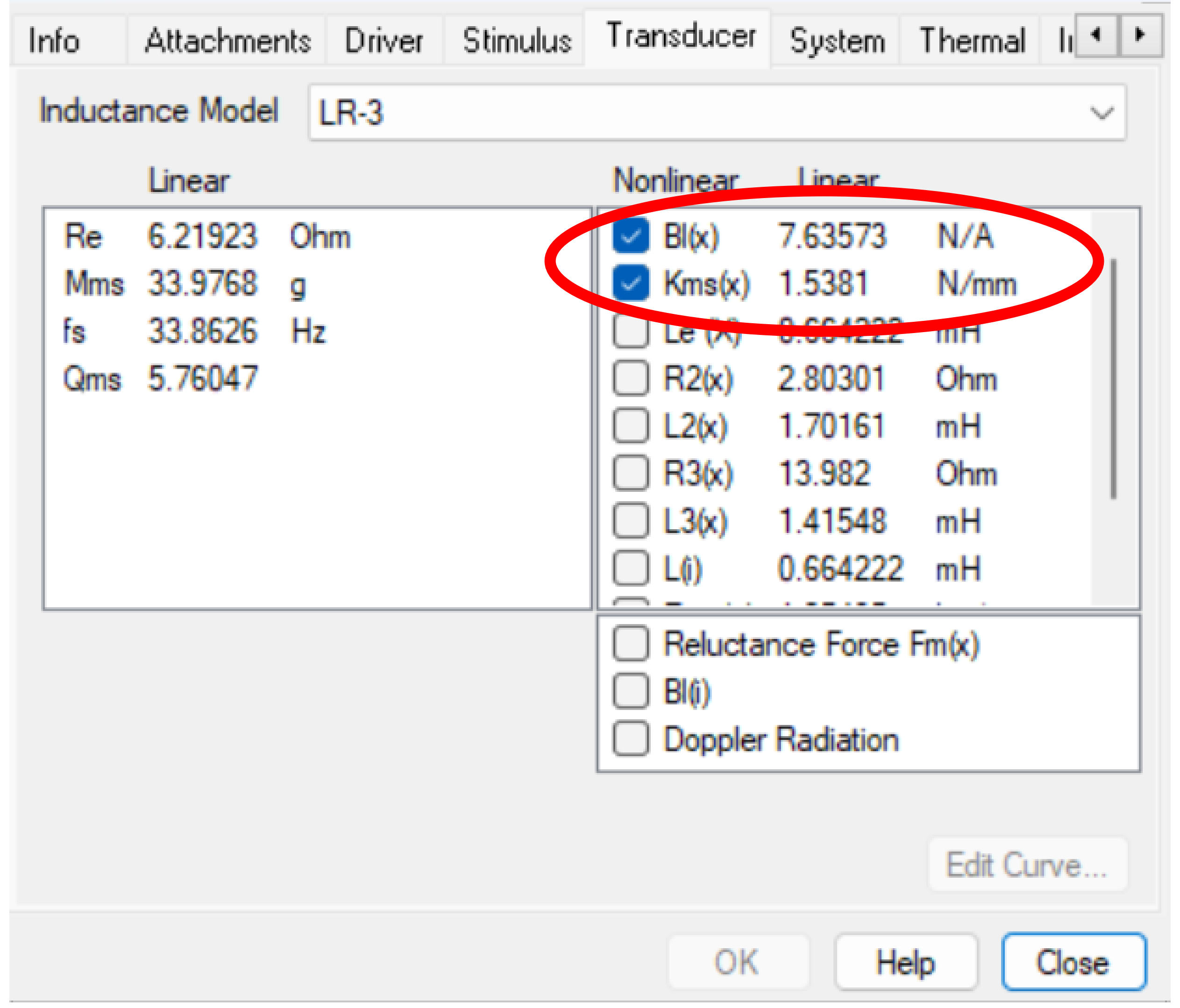
Interpretation

Applying simulatons

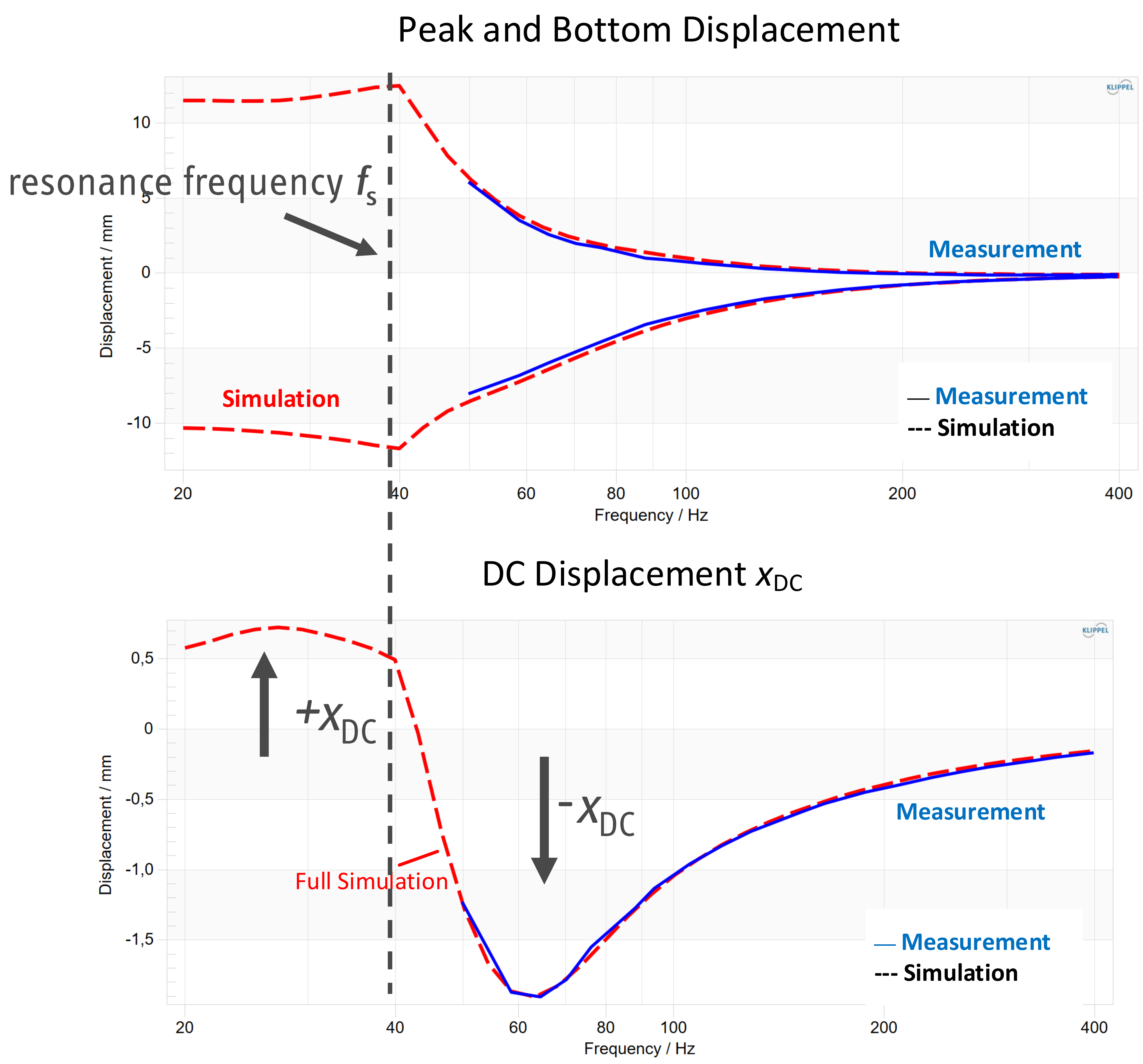
- **Goal:**
  - Perform targeted improvements on existing transducer motor, or
  - design a motor that meets defined target requirements
- **Procedure:**
  - Isolating nonlinearities → activating and deactiving individual parameters
  - Finding the dominant cause of nonlinear distortions
  - Distiguish between symmetric or asymmetric problems
- **Design Improvement:**
  - Identify what can be fixed in production
  - Apply design changes of dominant nonlinear parameters



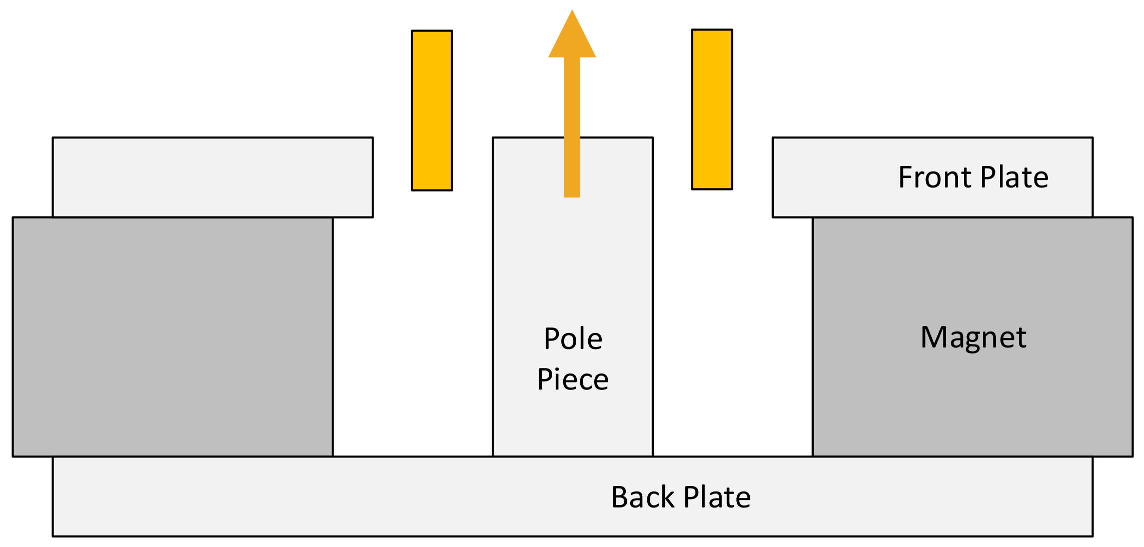
Klippel SIM module configuration

Interpretation

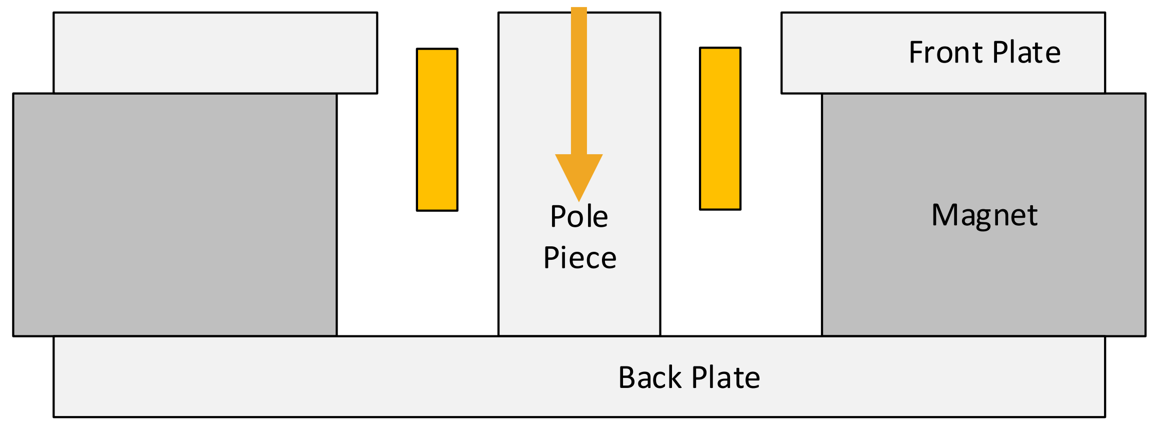
DC displacement



- <u>below resonance</u>: positive DC displacement

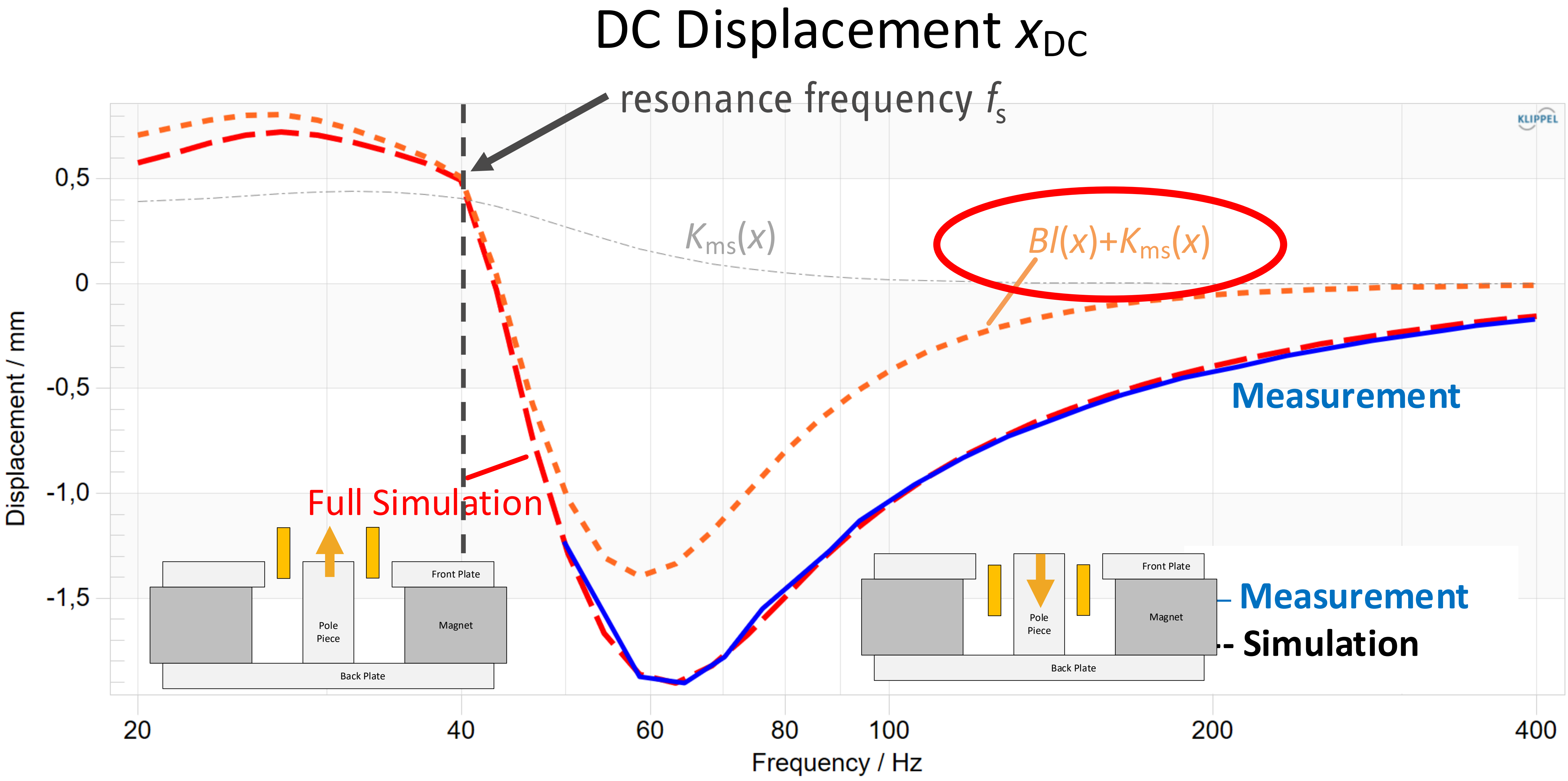


- <u>above resonance:</u> negative DC displacement

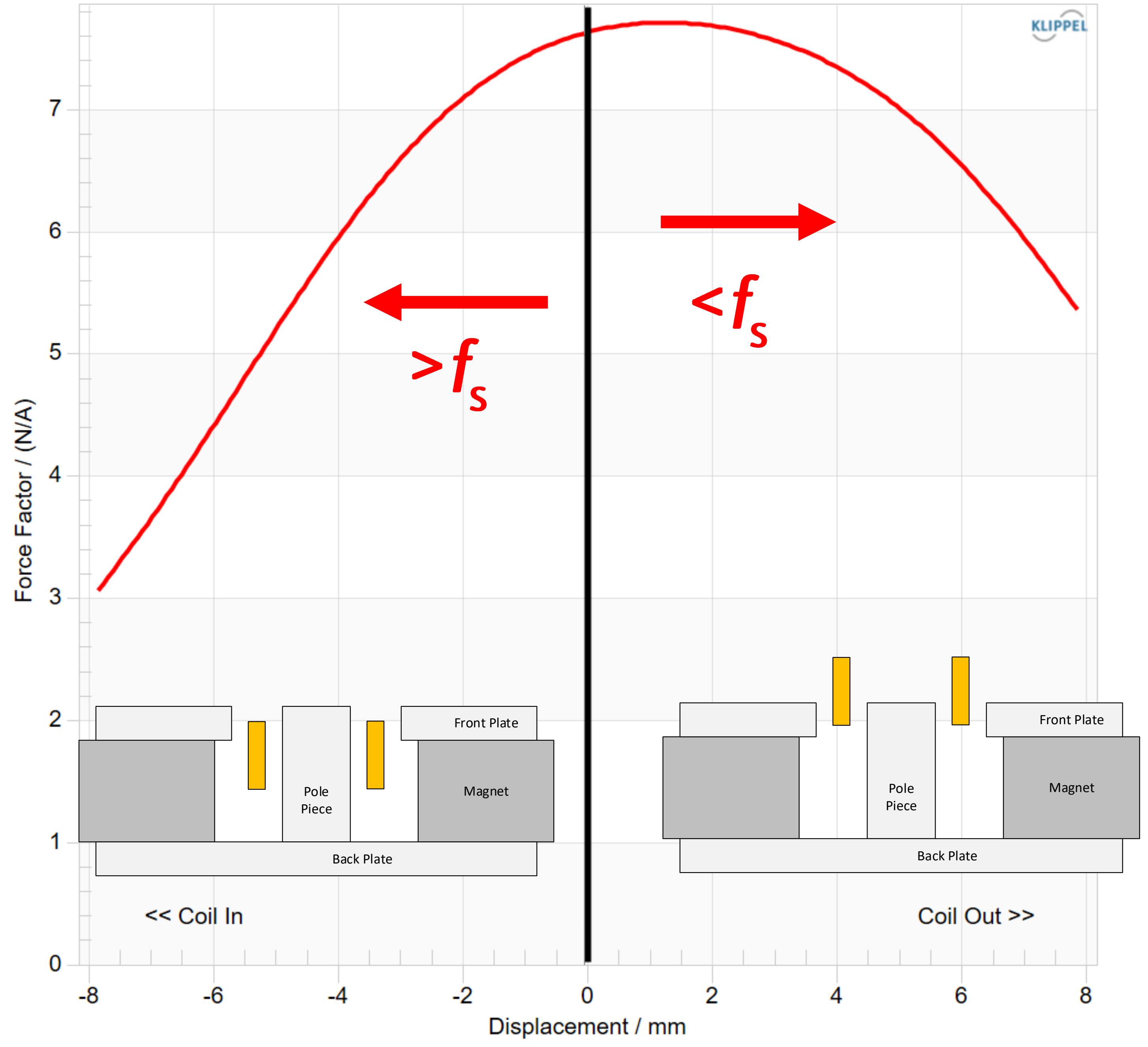


Interpretation – Isolating Nonlinearities

DC displacement



Measured Bl(x)



- <u>Bl(x) is the dominant cause</u> of DC displacement at low frequencies
- below resonance: DC displacement <u>towards from Bl(x) maximum</u>
- above resonance: DC displacement <u>away from Bl(x) maximum</u>

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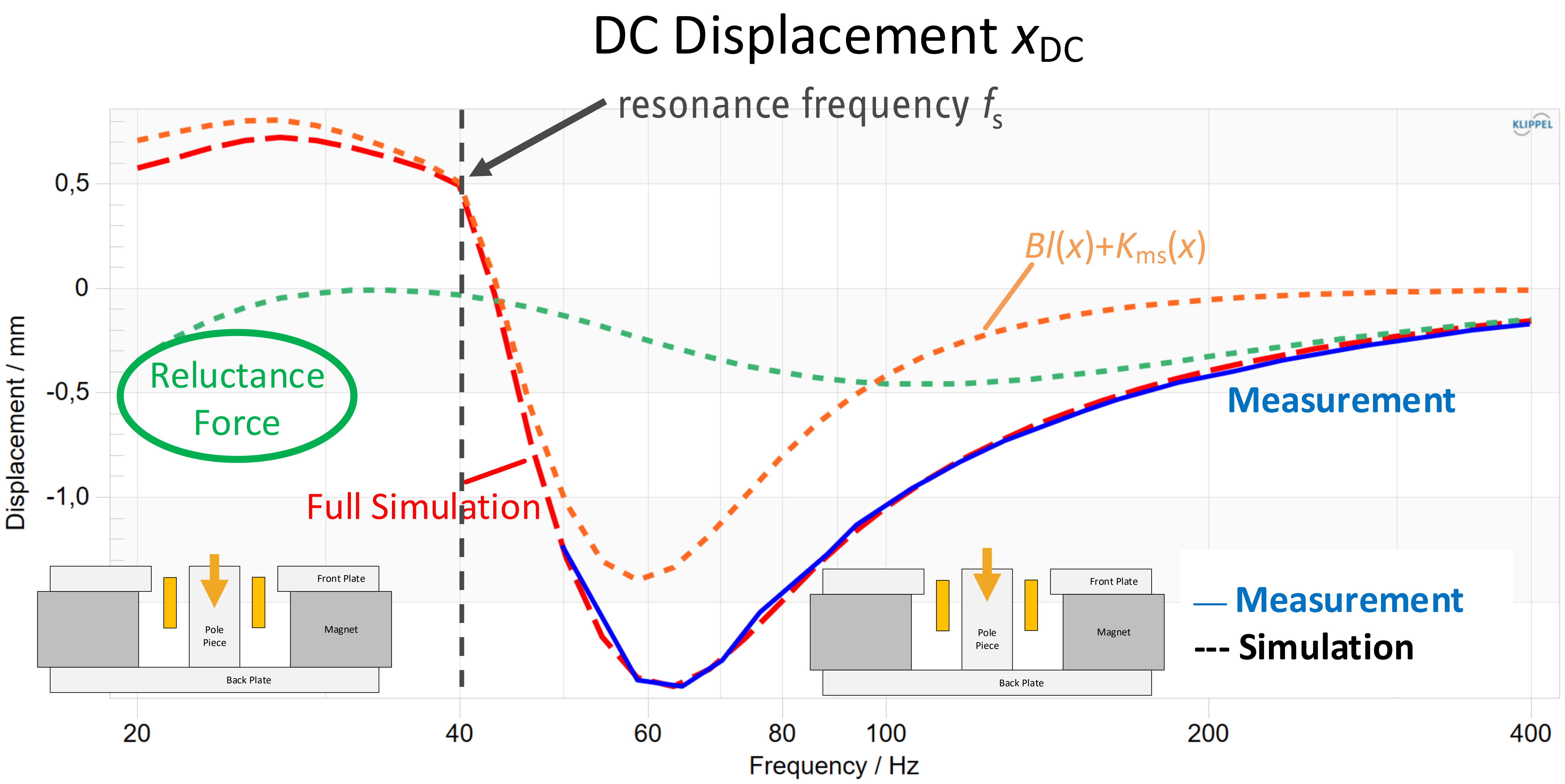
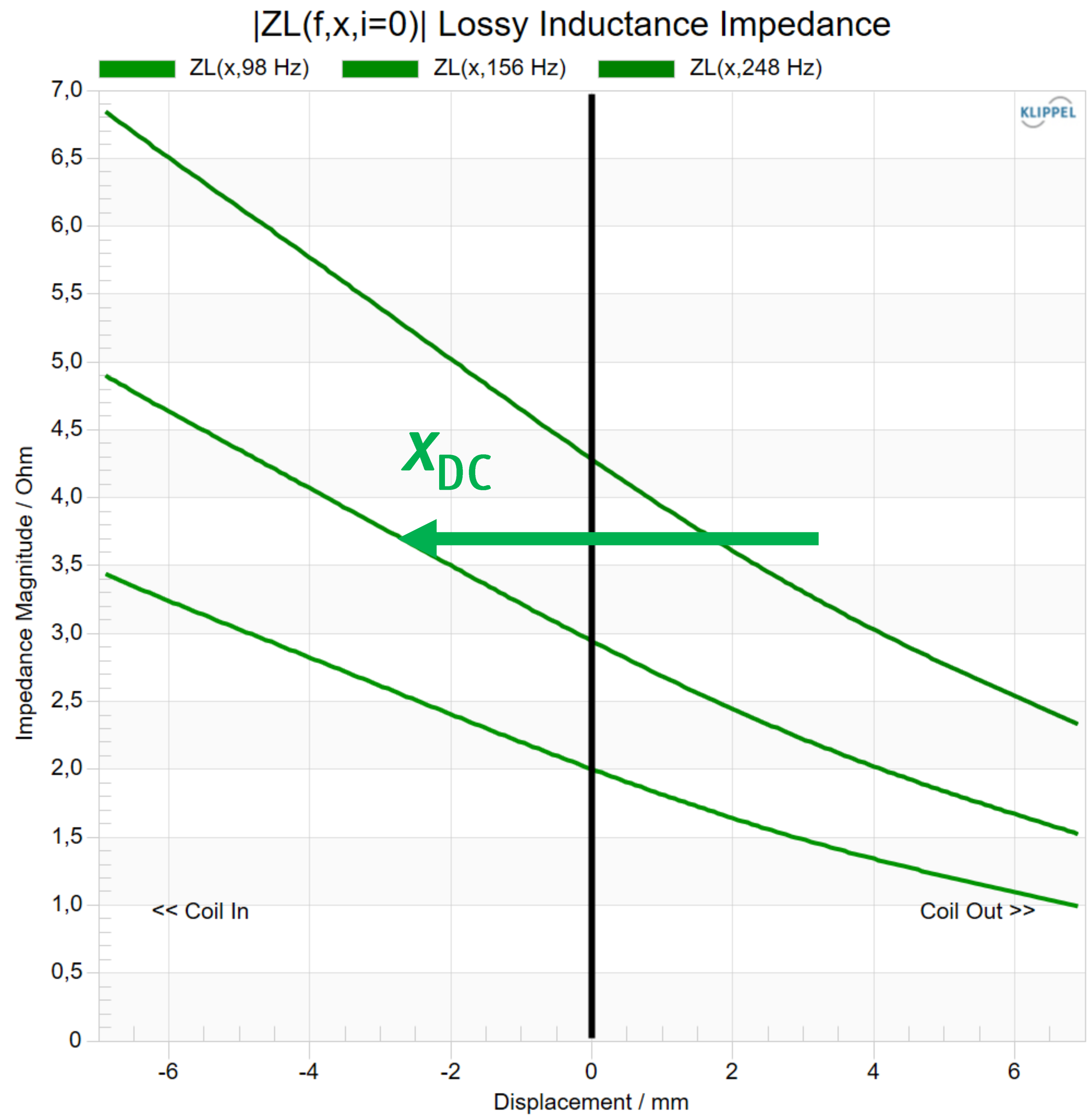
Interpretation - Isolating Nonlinearities

DC displacement



Reluctance Force:

$$F_r(f,x,i) \approx \frac{1}{2}\left(\frac{\mathrm{d}L(f,x)}{\mathrm{d}x}\, i^2\right)$$

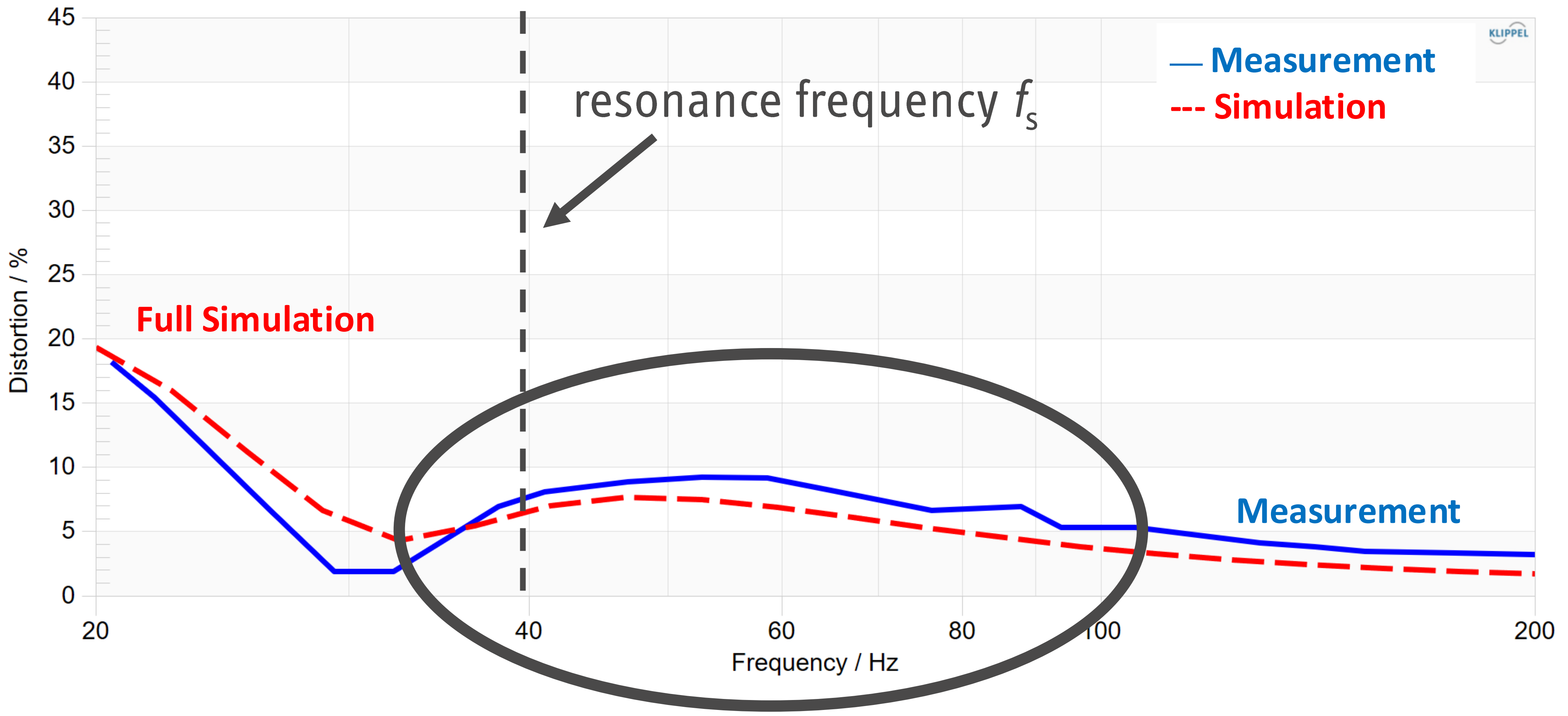


- reluctance force is <u>relevant above and below resonance</u>
- reluctance force acts in the direction of the <u>inductance maximum</u>
- negligible at resonance and very high frequencies due to low current

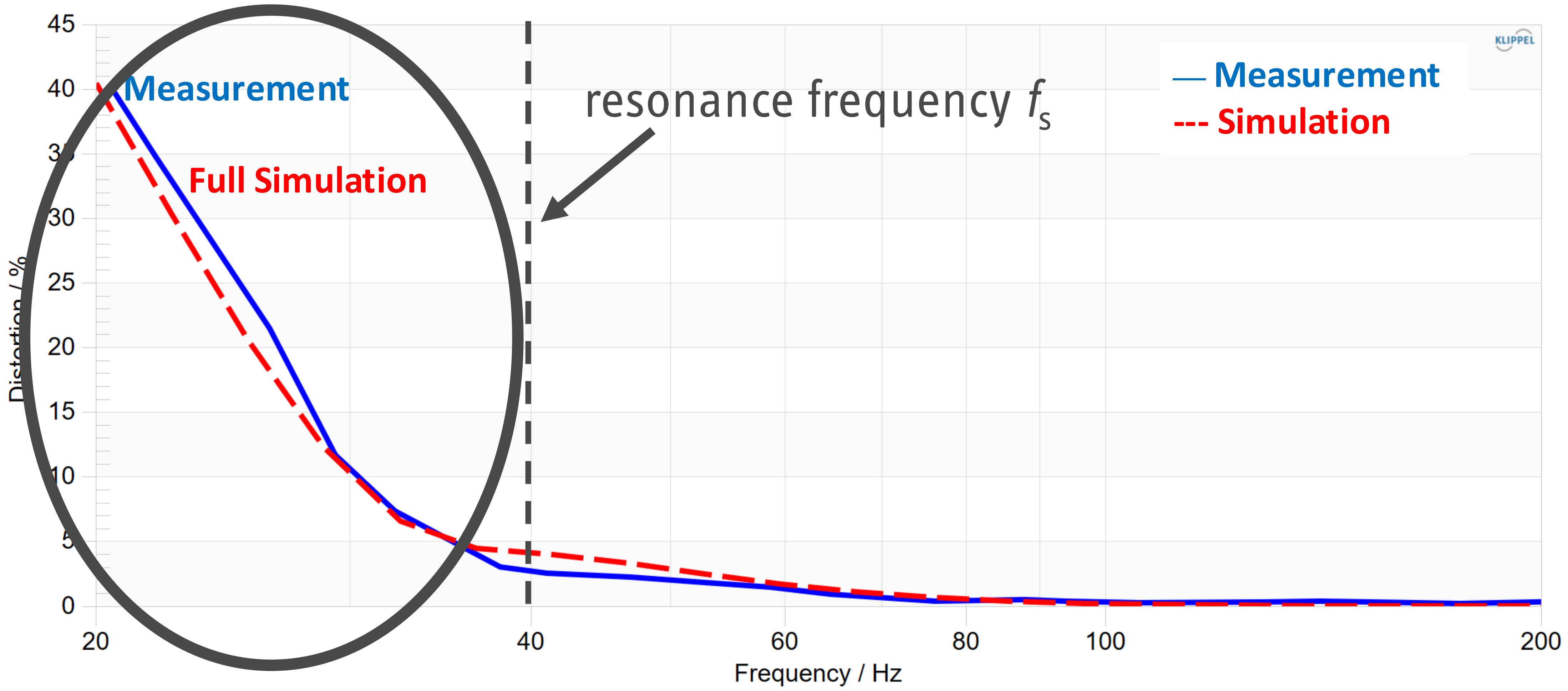
Interpretation

Harmonic Distortion

Relative 2nd order Harmonic Distortion



Relative 3rd order Harmonic Distortion

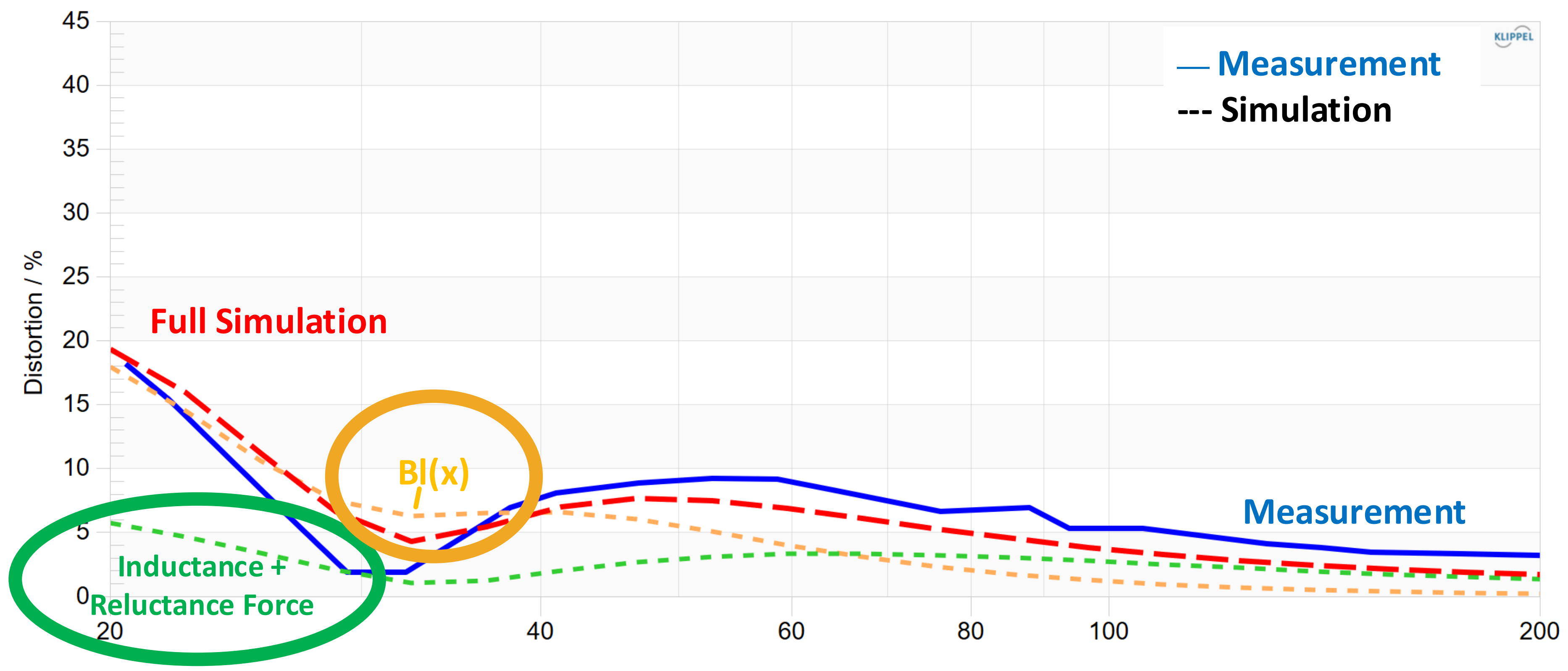


- <u>high THD below resonance</u> where displacement is high
- 3rd order harmonic distortion is dominant below resonance
- 2nd order harmonic distortion is dominant above resonance

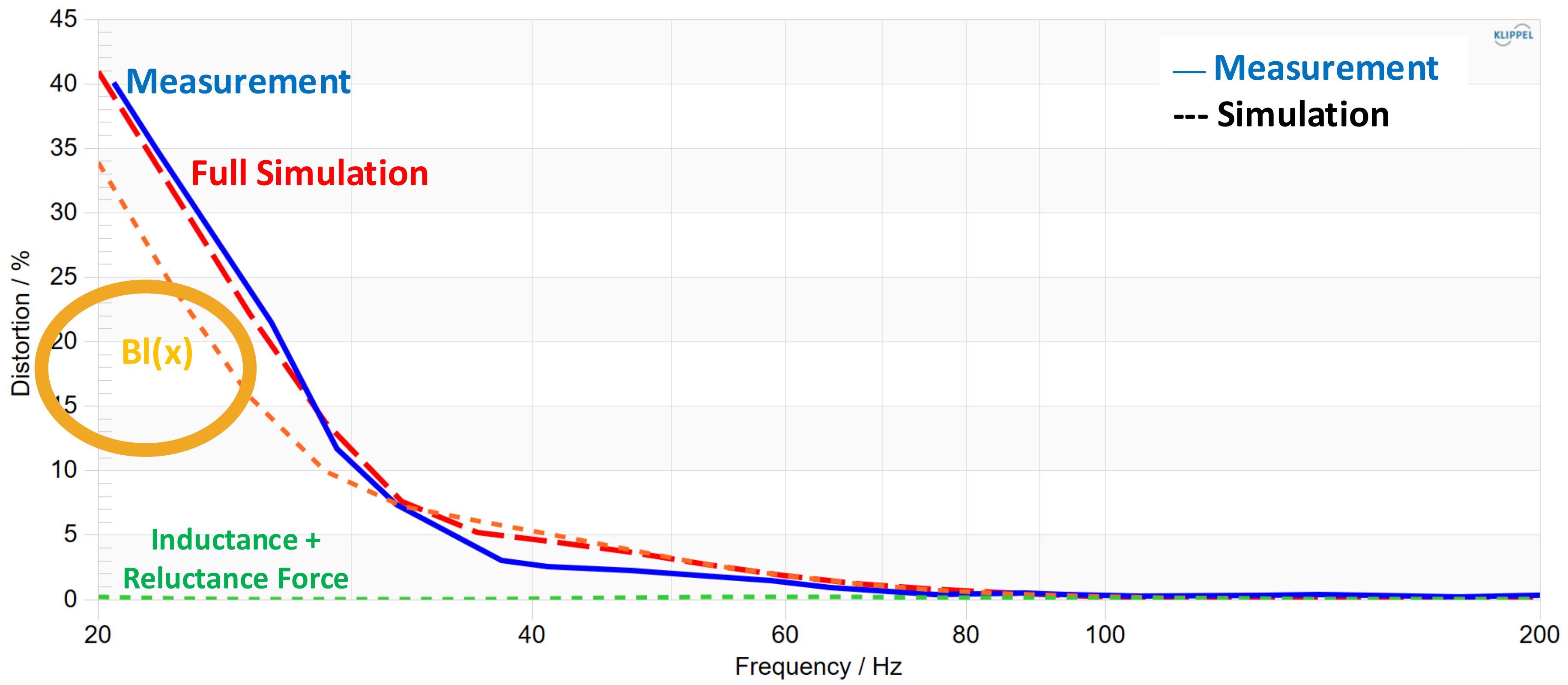
Interpretation - Isolating Nonlinearities

Harmonic Distortion

Relative 2^{nd} order Harmonic Distortion

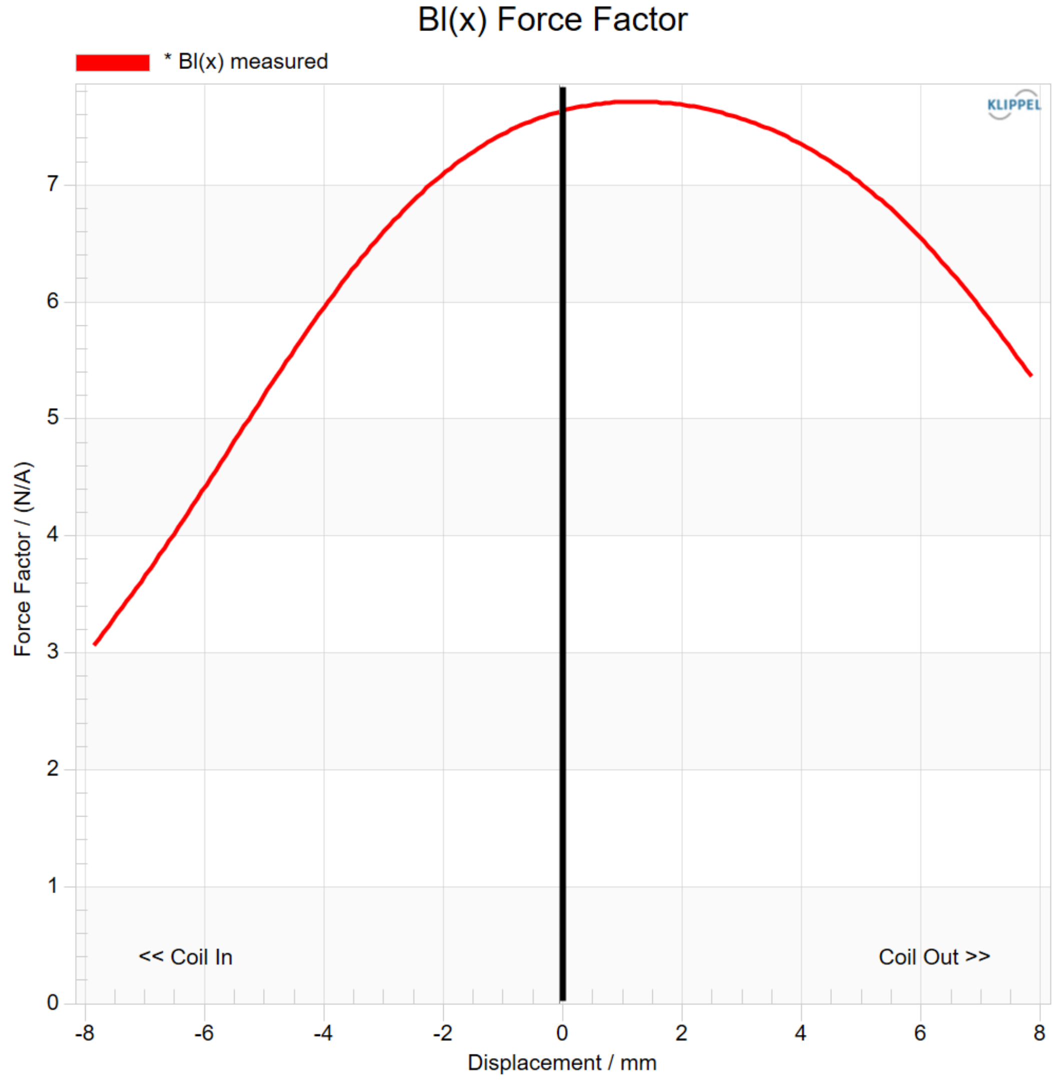


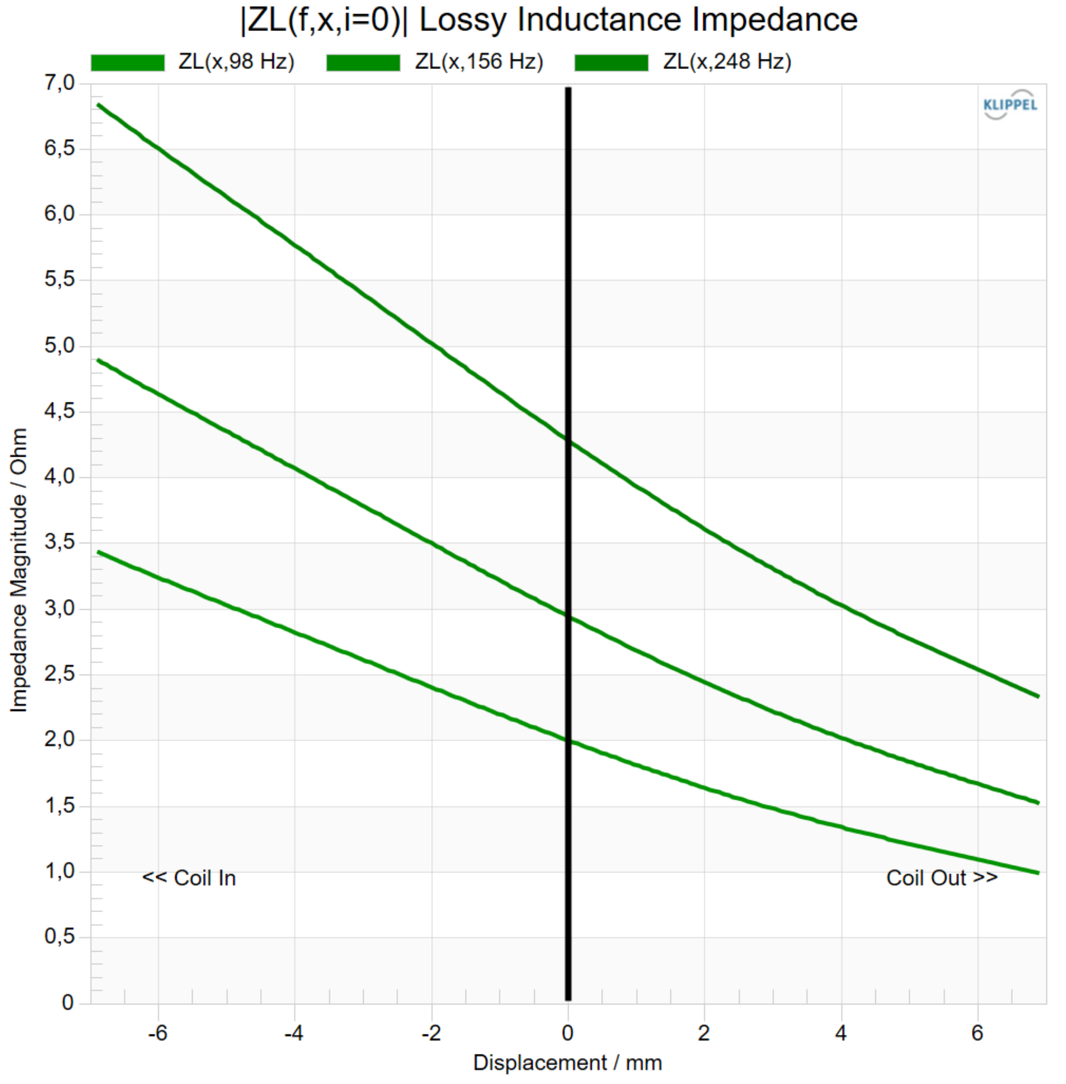
Relative 3^{rd} order Harmonic Distortion



- **<u>Bl(x) is dominant</u>**
- **Inductance and reluctance force produce low 2nd order distortion**

Focus on Bl(x) for improving the loudspeaker





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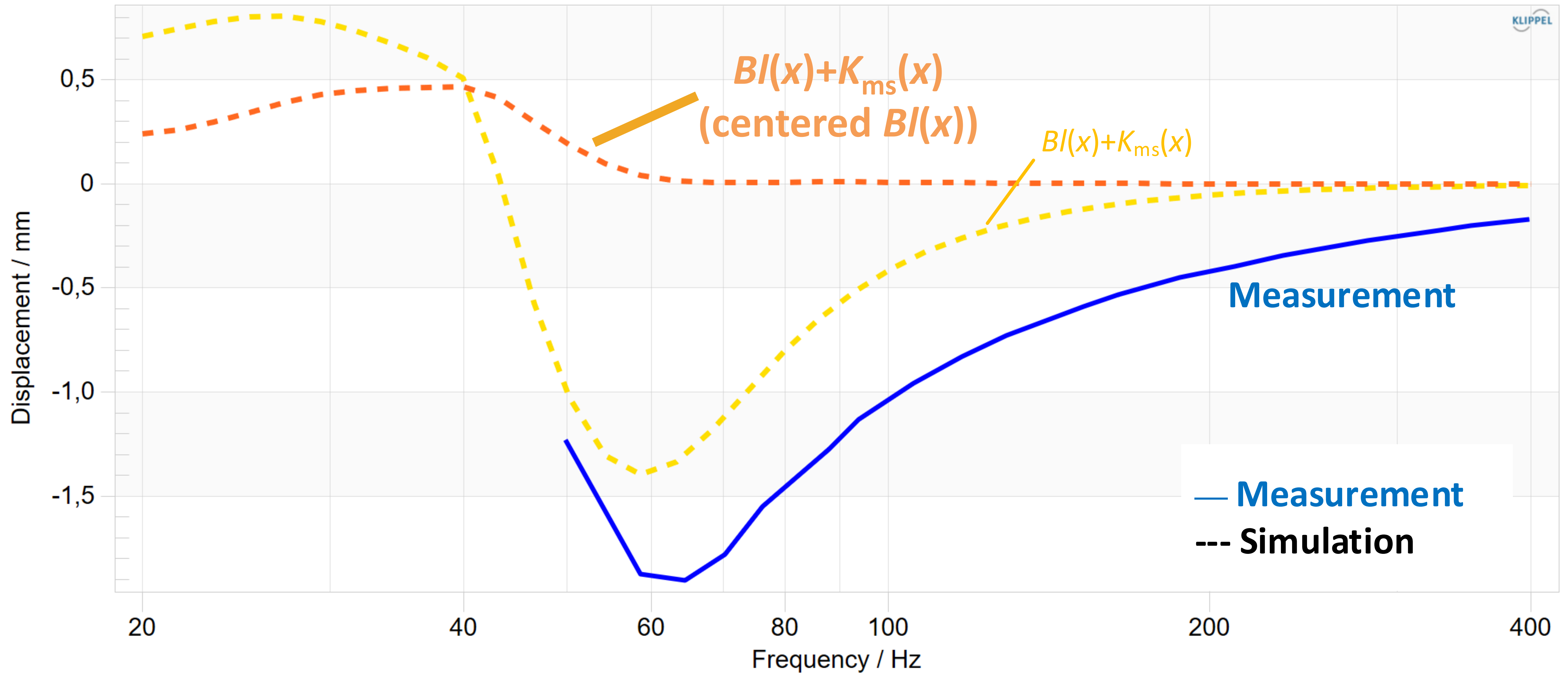
Interpretation - Improvement

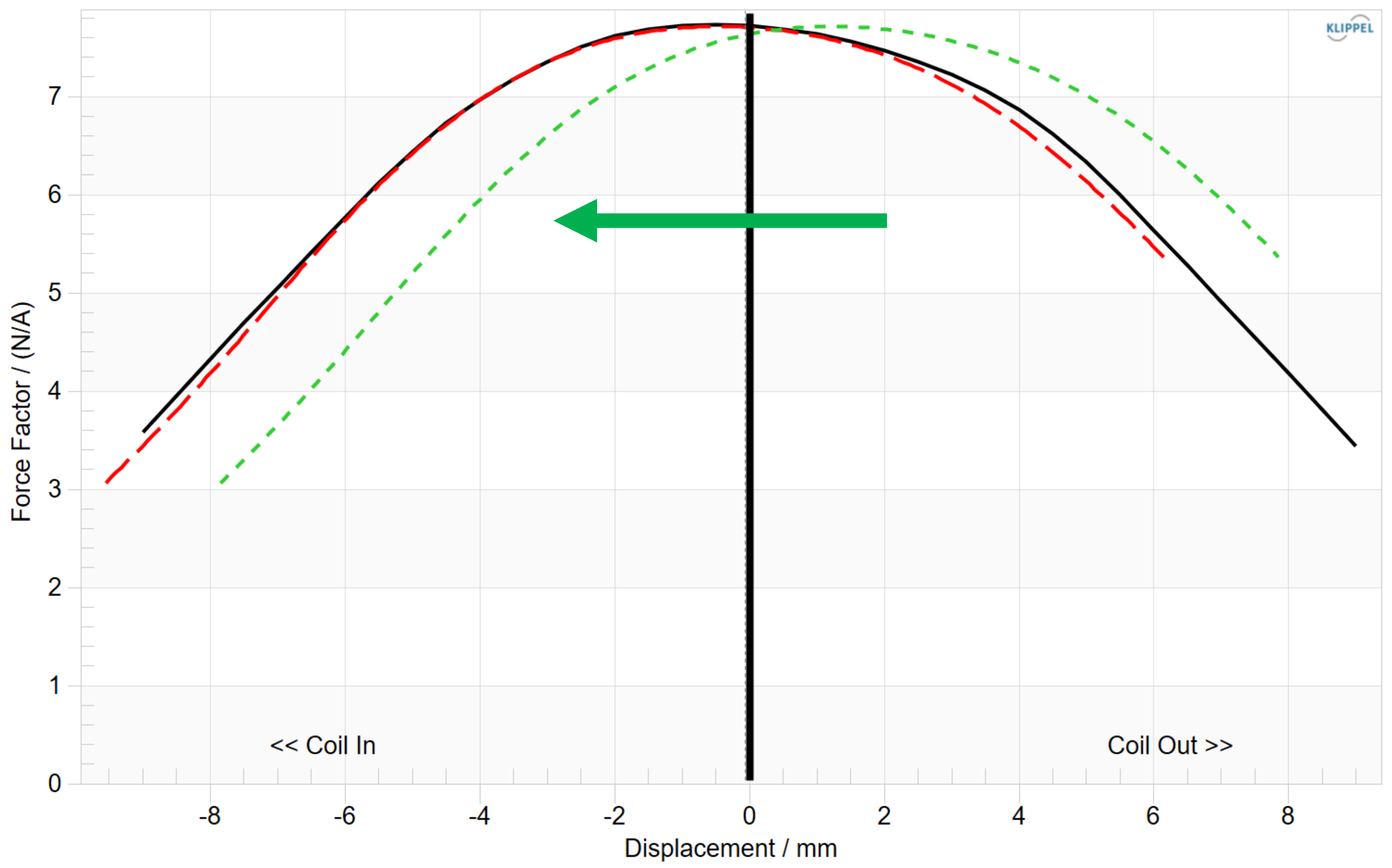
Reducing Bl(x) asymmetry

DC Displacement x_{DC}



- **DC displacement is reduced by symmetrizing Bl(x)**
- **cheap improvement**

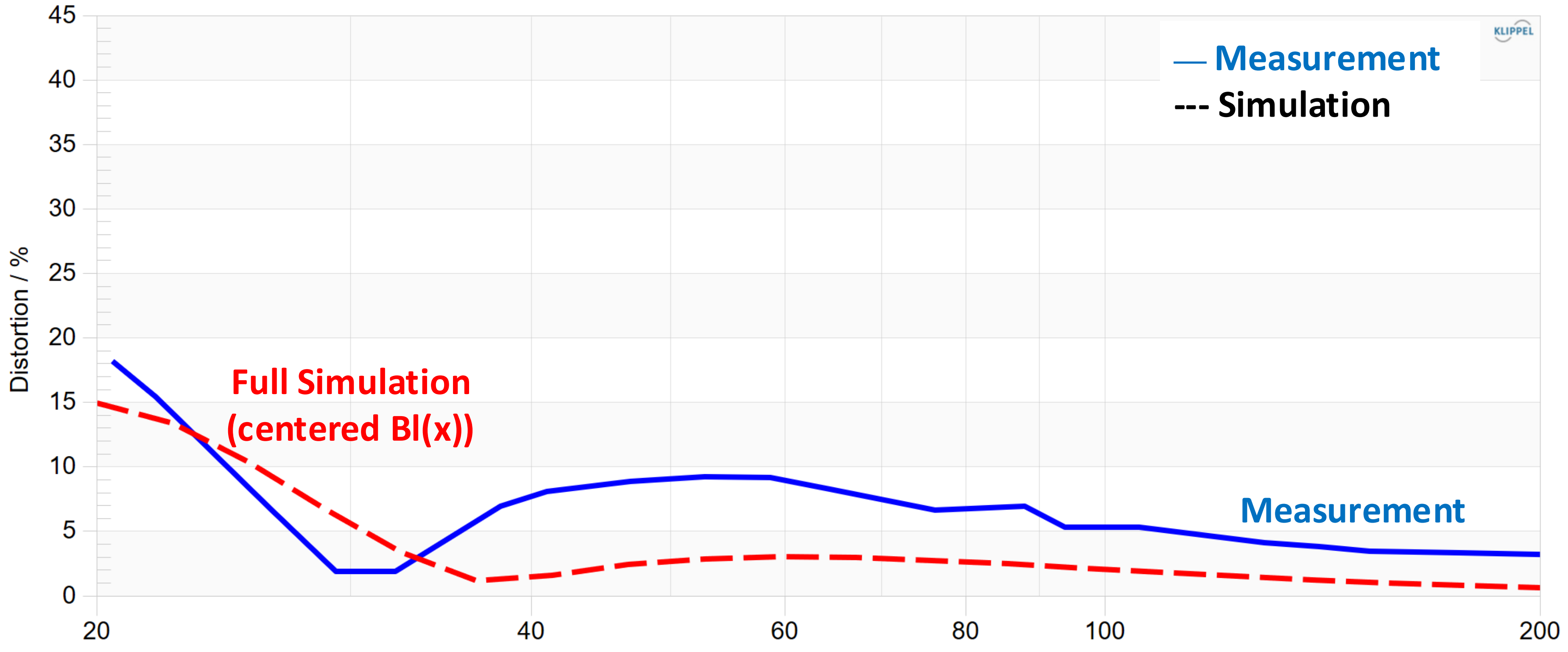
Force Factor $Bl(x)$



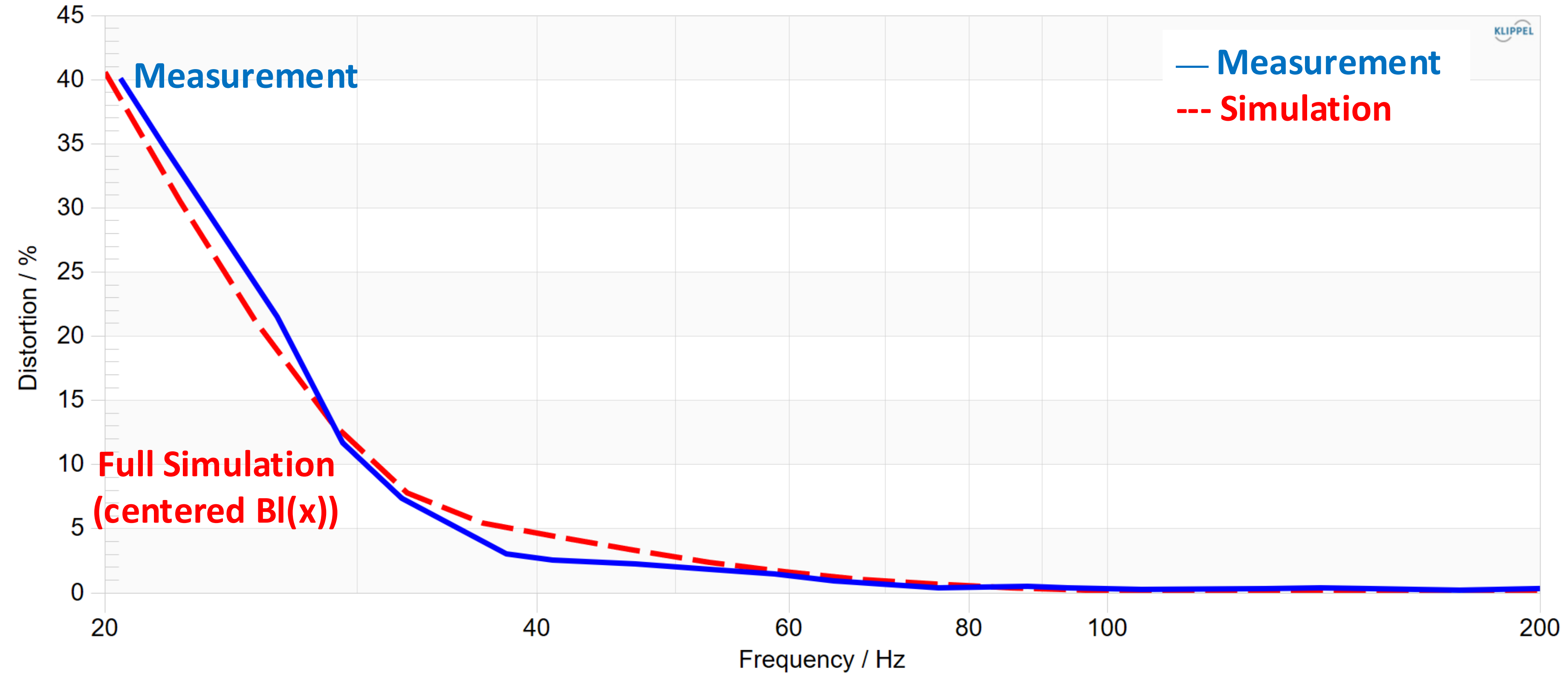
Interpretation - Improvement

Fixing Bl(x) asymmetry

Relative 2nd order Harmonic Distortion



Relative 3rd order Harmonic Distortion



- 2nd order harmonic distortion decreases
- 3rd order harmonic distortion does not change

Further improvements can be accomplished by

- using longer voice coil, reducing Bl(x) nonlinearity → reduces efficiency, increases inductance and reluctance force
- applying shorting material to reduce inductance → increases cost
- increasing stiffness to reduce DC displacement → reduces efficiency and voltage sensitivity
- using active control → requires DSP

→ FEA and Lumped Parameters aid in finding the optimal compromises quickly

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Key takeaways

- Validation of FEA against measurements remains essential
  - validate i.e., grid, configuration, material parameters, …
  - compensate offset in voice coil rest position
- Lumped parameters from FEA agree well with measured lumped parameters
- Nonlinear distortion measurements and simulations closely match at low frequencies
- Lumped parameters are highly valuable – they
  - allow performing fast parameter studies, by isolating nonlinearities
  - are applicable for simulations with complicated input signals (multi-tone, music, …)
- All required tools for validating FEA simulations are available

Outlook

- Incorporate magnetic saturation effects (flux modulation) into investigations
  - further increase agreement between FEA and measurement
- Extend investigation to the full transducer, including
  - suspension stiffness and losses
  - air flow resistances
  - other nonlinearities (i.e., $S_d(x)$)
- Compare measurements to transient (time-domain) FEA
  - perform full dynamic simulations
  - increase comparability to full dynamic measurement
- Extend nonlinear lumped parameter model to be valid at higher frequencies

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