Advanced FEM Simulation of Loudspeaker Performance: The Impact of Cone and Surround Materials

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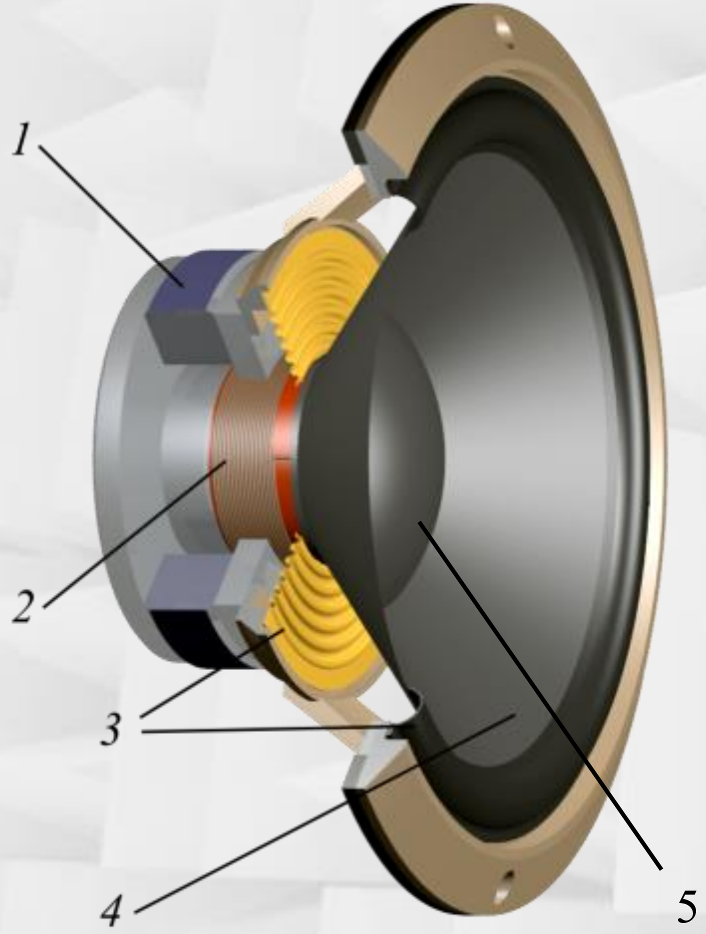
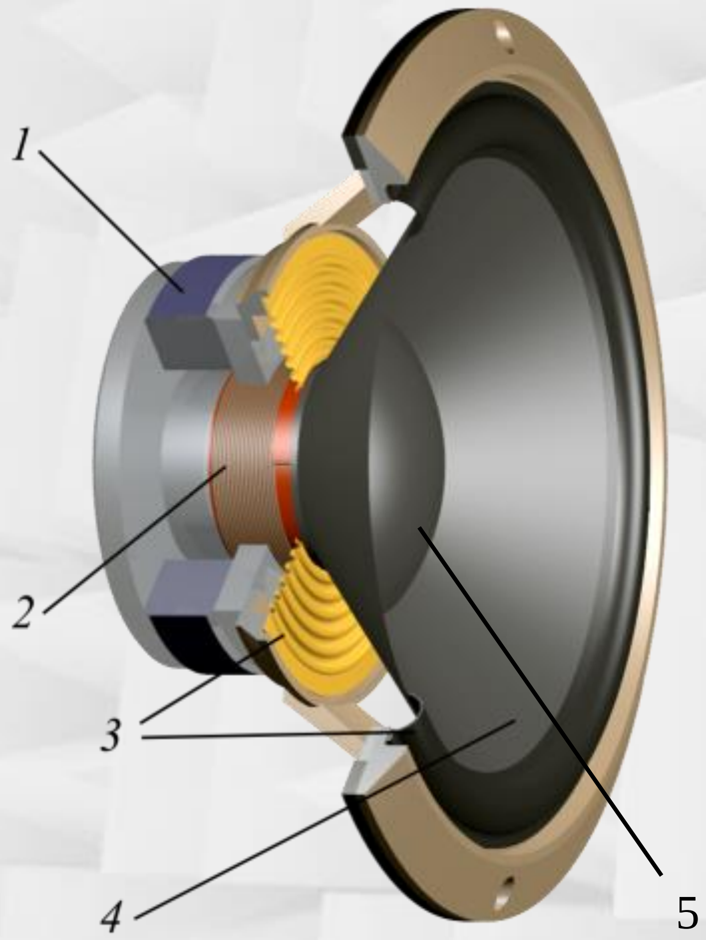
Music and Acoustic Engineering

Loudspeaker Components



1. Magnetic Circuit
   - Provides a magnetic field for the voice coil
2. Voice Coil
   - Electromotive Lorentz Force
3. Suspension System: Spider and Surround
   - Keeps the moving components centered
   - Provides restoring forces to bring to equilibrium
4. Cone
   - Radiates sound; converts electrical signals into sound waves
5. Dust Cap

Loudspeaker Components



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Membrane

Motivation and Aim

- The effectiveness of FEM hinges on its ability to replicate the loudspeaker’s behavior accurately.
- Variations in membrane materials can significantly influence performance.
- Accurately modeling loudspeakers allows for the exploration of new designs, utilizing new materials

This work aims to…

- Understand the magnitude of variations within membrane materials
- Deepen understanding of how material properties affect loudspeaker performance
- Present a robust FEM framework for analyzing loudspeaker materials

Approach

Analysis of Material Mechanical Properties → FEM Optimization of Material Properties → Modeling of Loudspeakers → Measurement Verifications

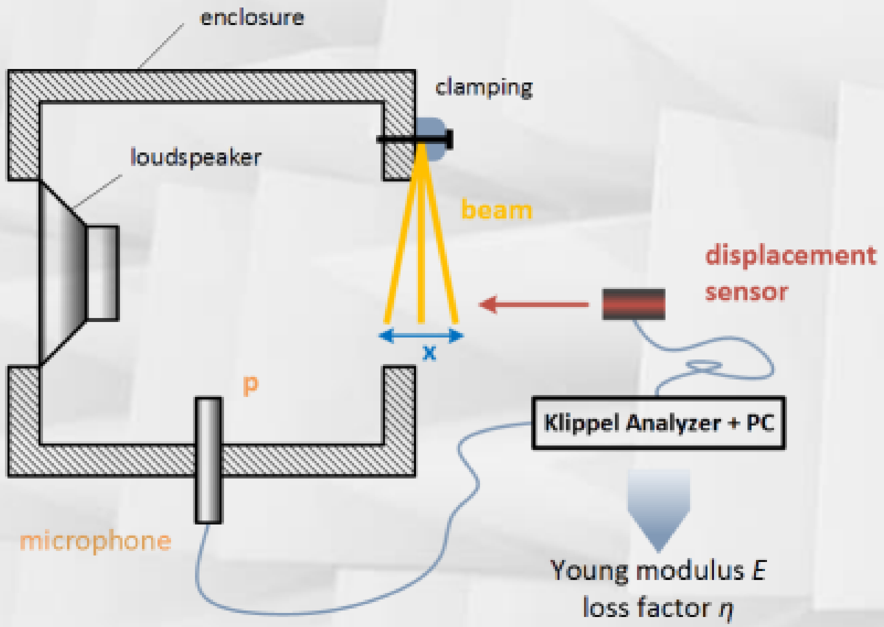
Stage 1 (Analysis of Material Mechanical Properties; FEM Optimization of Material Properties)

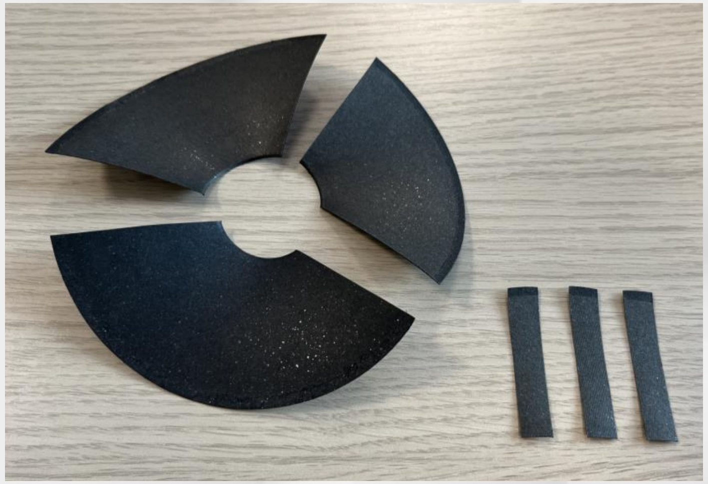
Stage 2 (Modeling of Loudspeakers; Measurement Verifications)

Klippel® Material Parameter Measurement (MPM)

Analysis of Materials | FEM Optimization of Properties | Modeling of Loudspeakers | Measurement Verification

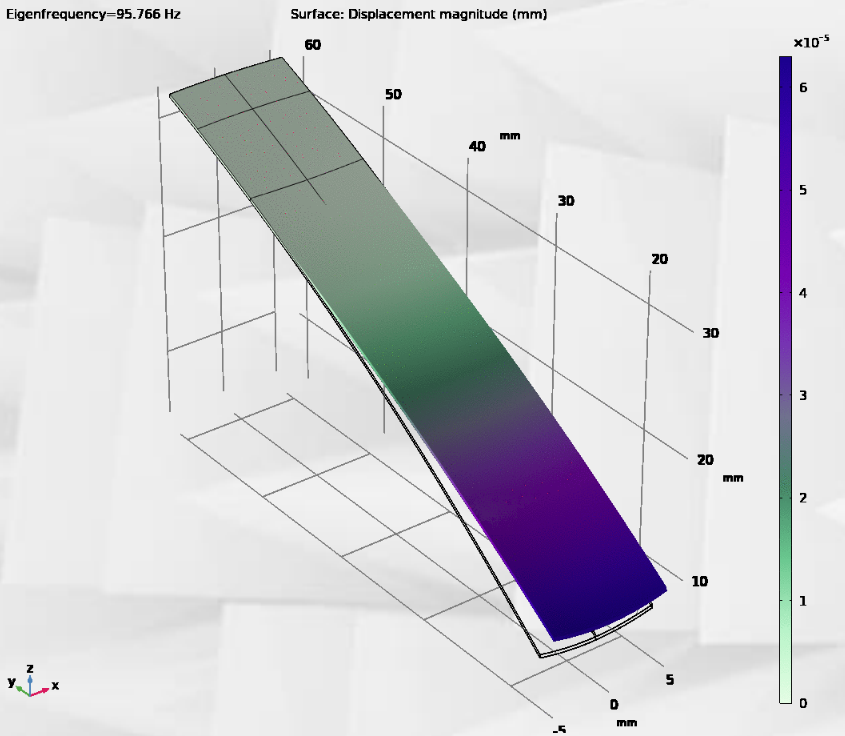
- The MPM module excites a strip of material by a sine sweep of the loudspeaker.
  - **Sound pressure p(t)** and **displacement x(t)** are measured simultaneously.
  - Transfer Function H(f) = X(f)/P(f) → Resonance Frequency Fs





Cone Material FEM Models

- Resonance frequencies were used as input in COMSOL
- 3-D model
- Eigenfrequency study with optimization node to calculate the materials Young's modulus.



Parameters

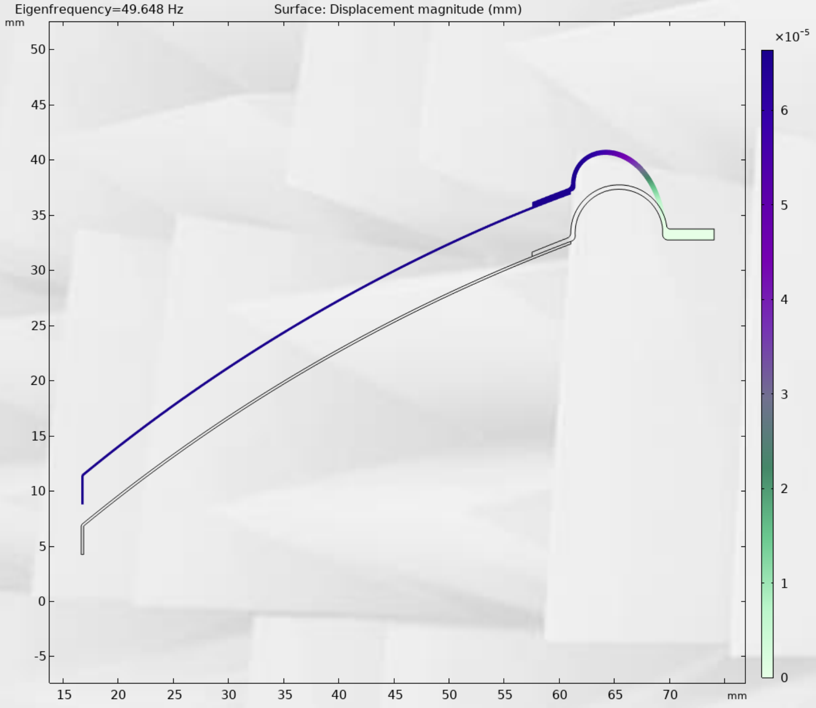
Label: Parameters 1

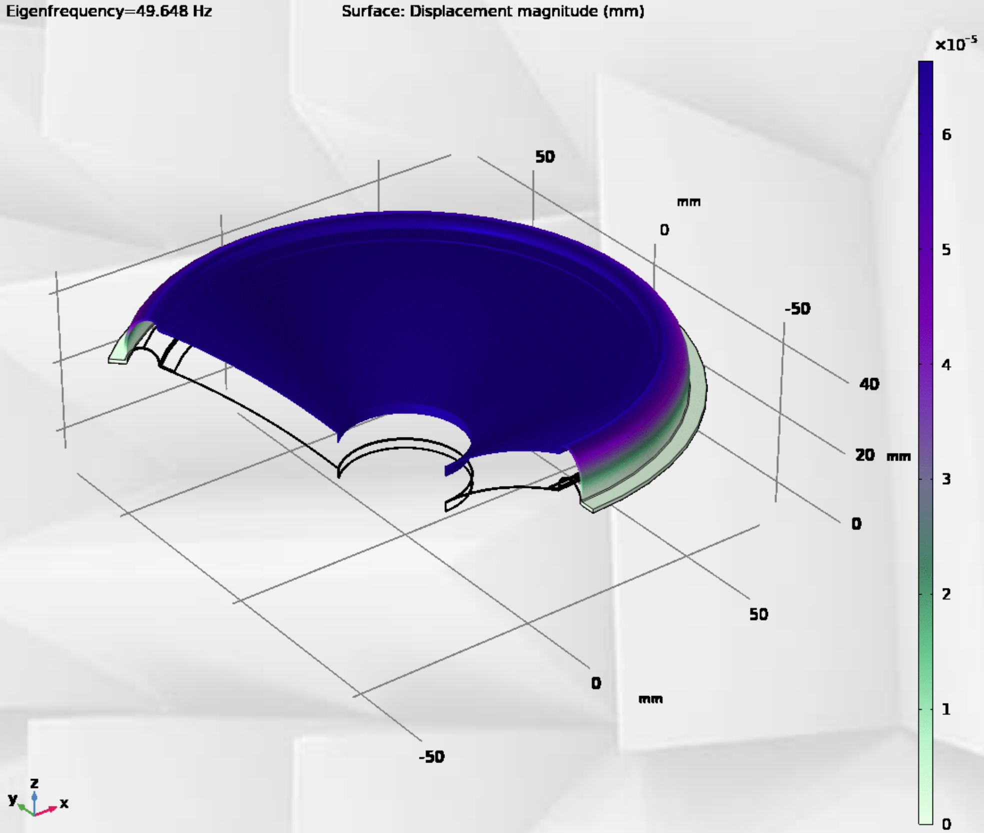
Parameters

Name	Expression	Value	Description
fres	41.47 [Hz]	41.47 Hz	Average Resonance Freq of 3 Measurements
rhoCone	1175.3 [kg/m^3]	1175.3 kg/m³	Density Material
update	1.3750	1.375	Optimized Update Parameter
eCone	2 [GPa]*update	2.75E9 Pa	

Surround Material FEM Models

- COMSOL model (2-D axisymmetric model) to find the surround Young's modulus.
- Eigenfrequency study with optimization node to calculate the materials Young's modulus.





Loudspeaker Selection

Analysis of Materials > FEM Optimization of Properties > **Modeling of Loudspeakers** > Measurement Verification

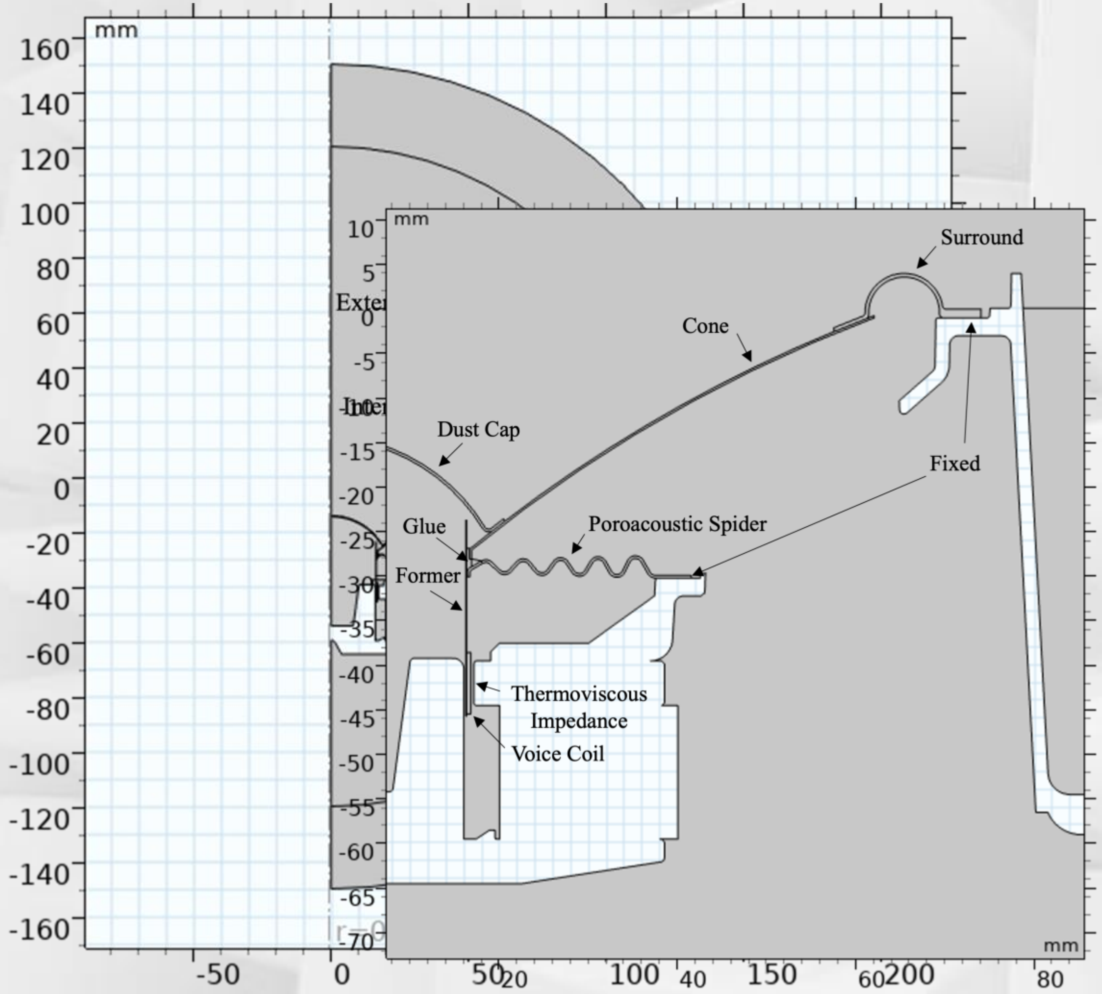
	Cone Material	Surround Material	Diameter	Apex
Loudspeaker #1	15% Mica Paper filtered	Nitril Rubber	160 mm	Dust Cap (Fiberglass)
Loudspeaker #2	Fiber glass	Nitril Rubber	160 mm	Dust Cap (Fiberglass)
Loudspeaker #3	10% Mica Paper filtered	Polyurethane Foam	130 mm	Whizzer

Loudspeaker #1

Loudspeaker #2

Loudspeaker #3

Loudspeaker FEM Models - Physics



- Electrical Domain
  - **Electrical Circuit** interface, utilizing measured lumped parameters
- Mechanical Domain
  - The **Solid Mechanics** interface models the structural dynamics of the loudspeaker moving components.
- Acoustic Domain
  - **Pressure Acoustics, Frequency Domain** interface simulates the acoustic pressure waves generated by the loudspeaker.
    - *Perfectly Matched Layer (PML)* to allow calculation of the pressure at any distance and angle.
    - *Thermoviscous boundary layer impedance* applied to consider losses due to thermal and viscous dissipation in thin regions.

Loudspeaker FEM Models - Studies

1. Eigen Frequency Study → Resonance frequency of the membrane.
2. Stationary Study → Spider component characterization for impedance matching
3. Frequency Domain Study → Frequency response and impedance
4. Additional Studies:
   - Frequency Domain Studies
     - Parametric sweeps → Effects of material parameter changes

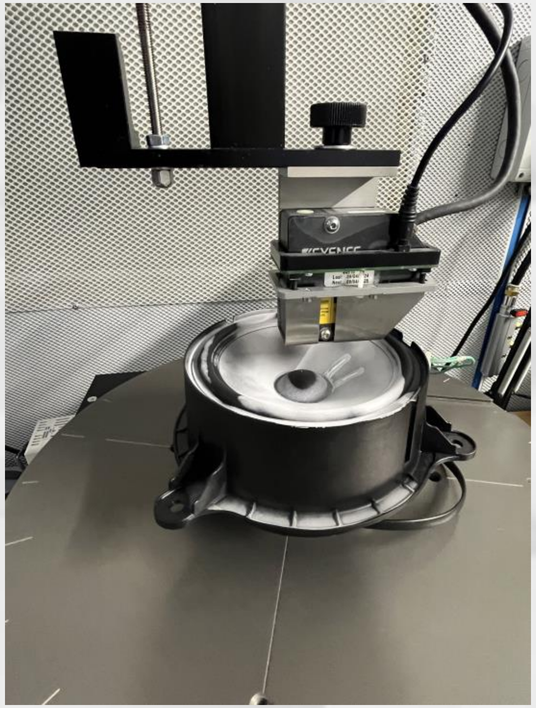
M&M

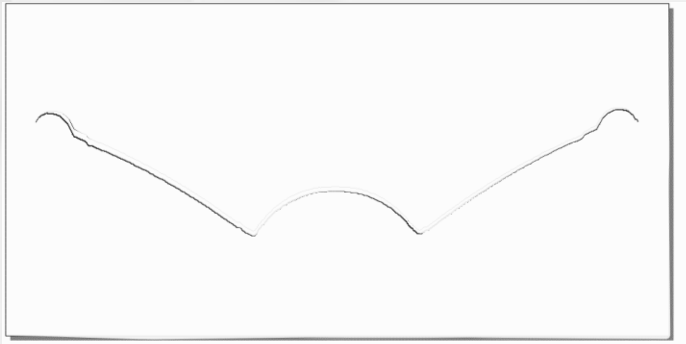
Physical Loudspeaker Measurements

Analysis of Materials | FEM Optimization of Properties | Modeling of Loudspeakers | **Measurement Verification**

Klippel® Scanning Vibrometer (SCN)

- Laser displacement sensor over the loudspeaker
- Precise measurement of the transducer's surface in polar coordinates
- Used for comparison with simulated deformations



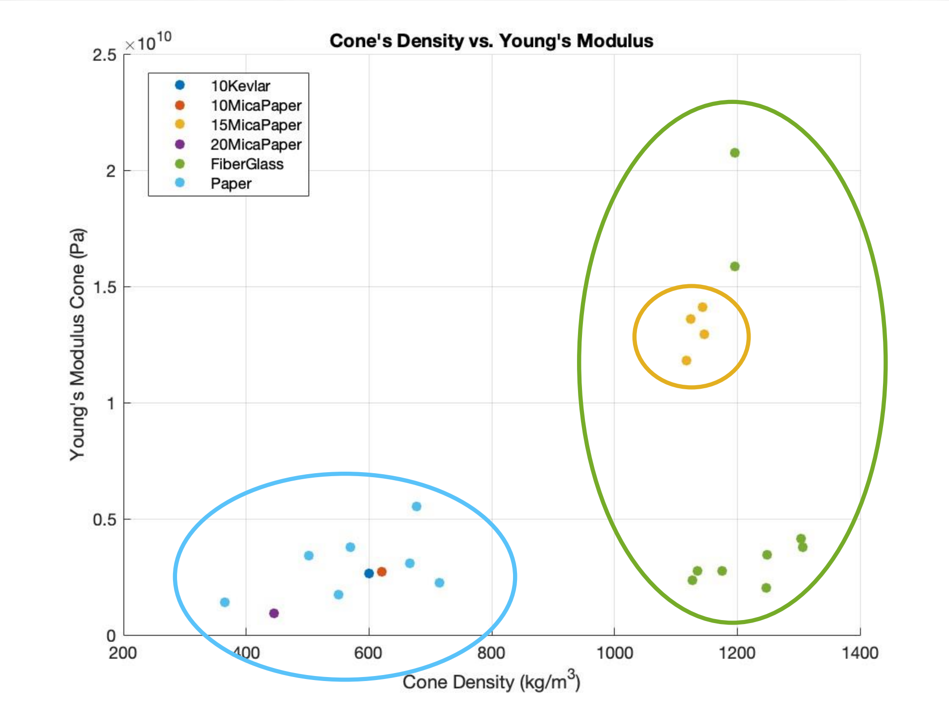


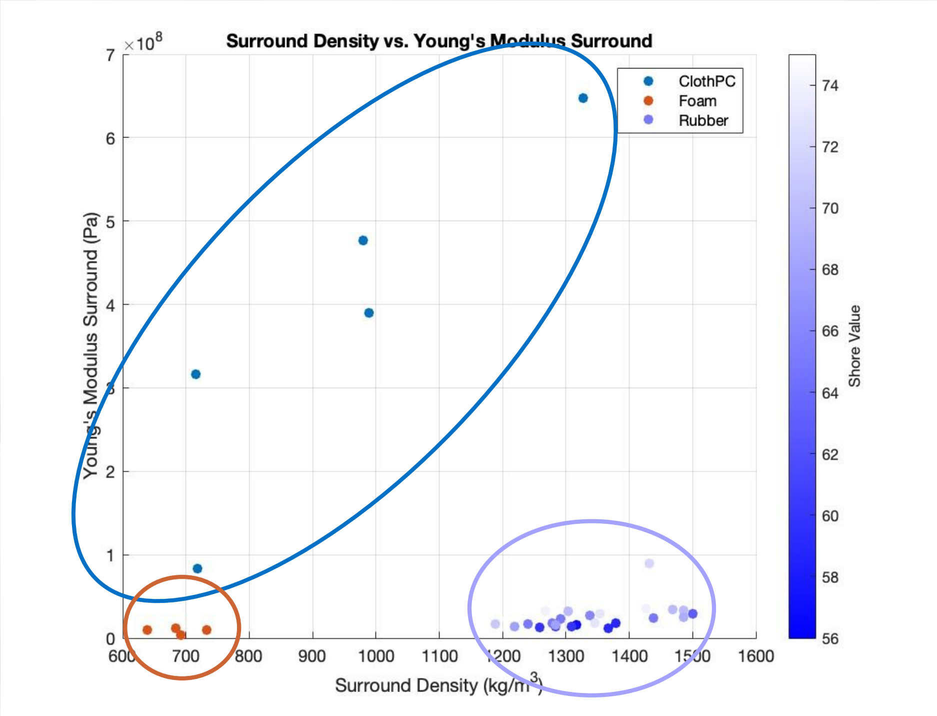
SCN Deformation Measurement at 180 Hz of Loudspeaker #1

- Standard impedance measurements
- Acoustic response in a semi-anechoic chamber

Cone Materials

Analysis of Materials | FEM Optimization of Properties | Modeling of Loudspeakers | Measurement Verification





- Paper
  - High Variability in density
    - (365 to 720 kg/m^2)
  - E_{Cone} increase with increased density
- Paper +10% Mica and Paper +10% Kevlar
- Paper +15% Mica
- Fiberglass

- Poly-Cotton Cloth
  - Very high variability: due to production processes, weaving patterns, or resins used.
- Foam
- Rubber

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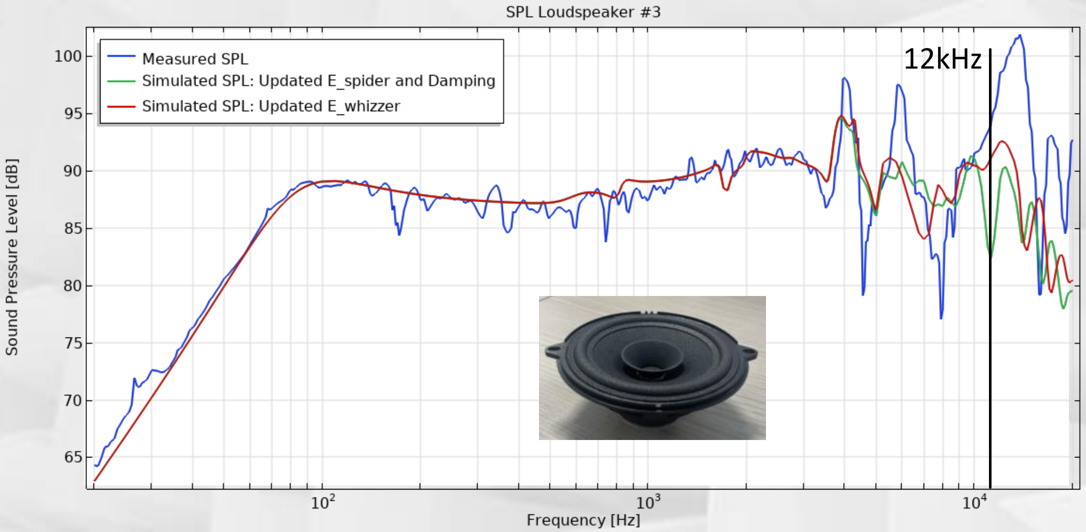
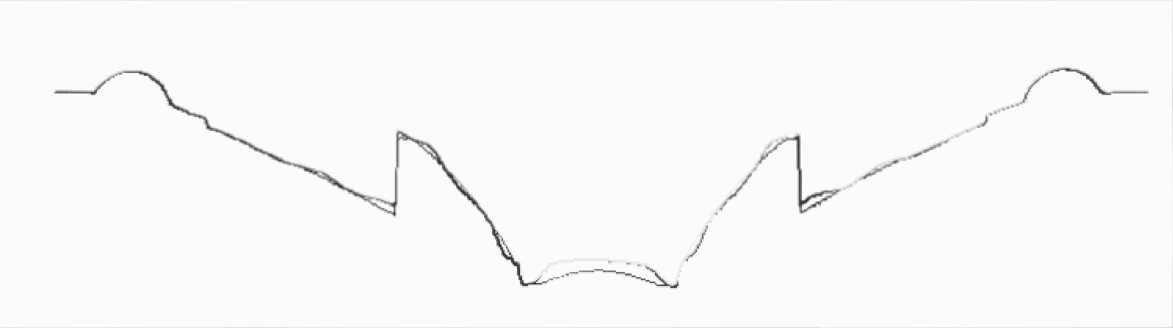
Loudspeaker #3

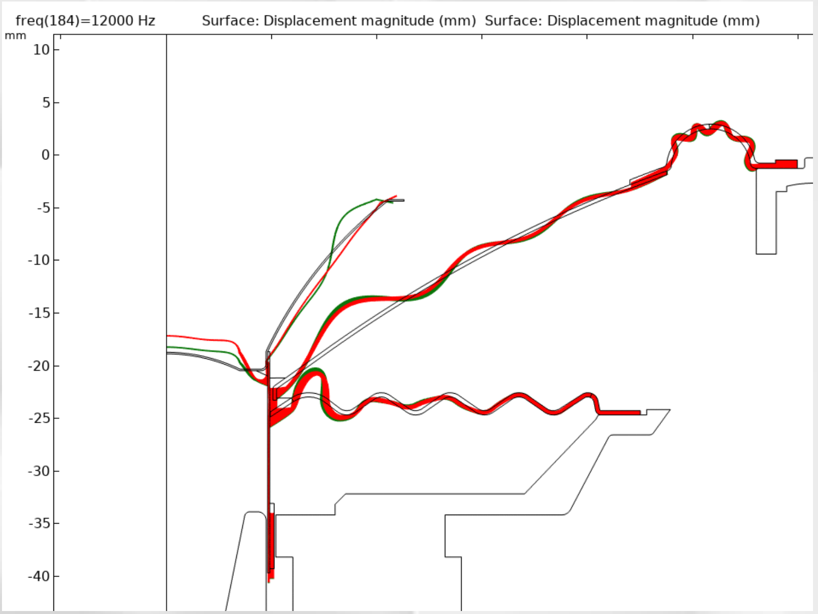
Analysis of Materials → FEM Optimization of Properties → **Modeling of Loudspeakers** → **Measurement Verification**



- The effect of the whizzer
- Lack of matching at higher frequencies → Increased $E_{Whizzer}$



Measured SCN Deformation at 12 kHz



Simulated Deformation at 12 kHz

Before updating $E_{Whizzer}$ & **Updated $E_{Whizzer}$**

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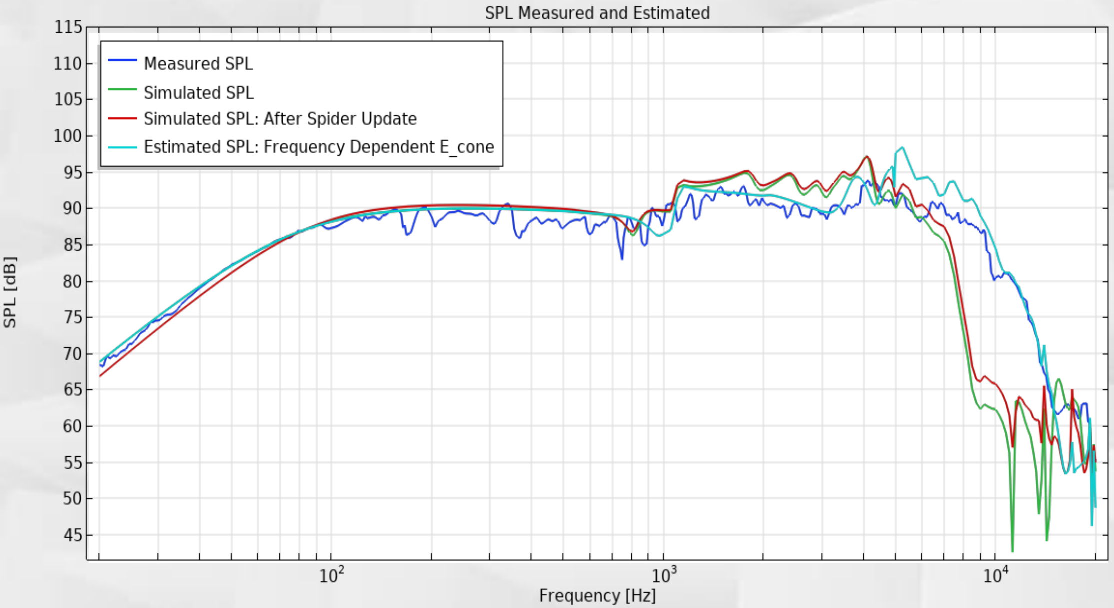
Conclusions

- Goal: Advance the understanding of loudspeaker design through a detailed analysis of cone and surround materials
- Mechanical properties of loudspeaker membrane materials, particularly Young’s modulus, significantly influence acoustic performance.
- Material Behavior:
  - Predictable: Paper, foam.
  - Variable: Cloth, fiberglass.
- Strong agreement between measured and simulated frequency responses.

Thank you!

Loudspeaker #2



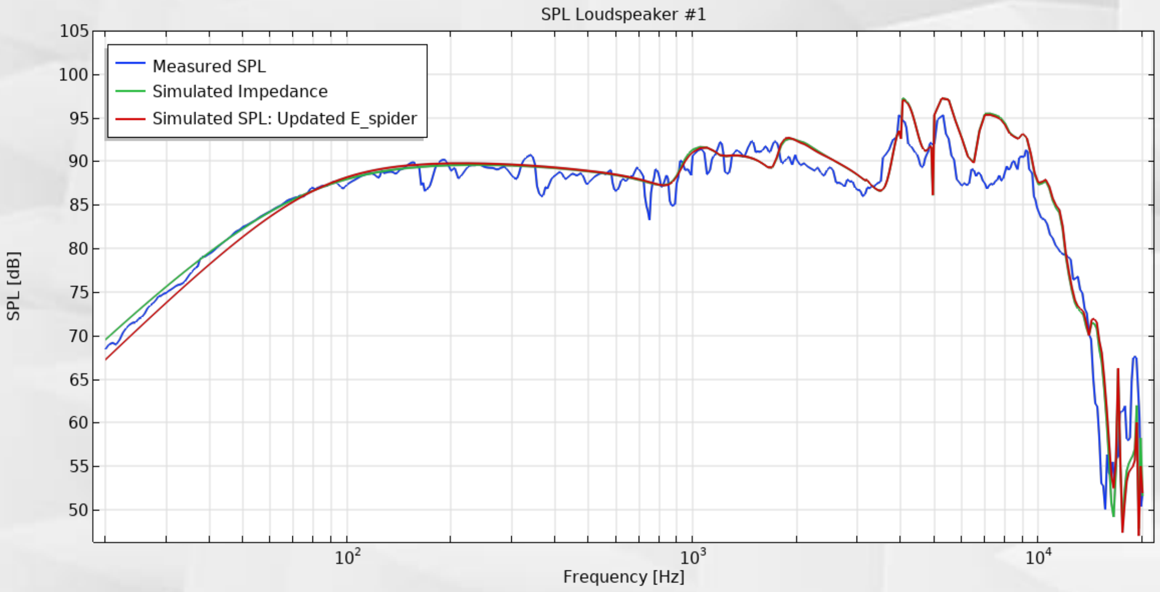
- Loudspeaker #2 showed a lack of matching in higher frequencies
  - It was found that E_{Cone} was valid only at low frequencies, and thus frequency dependent.
  - A ramp function was applied to E_{Cone} material

- Frequency dependence of some materials such as fiberglass should be considered

Cone: Fiberglass
Surround: Nitril Rubber 60A

Loudspeaker #1

Analysis of Materials | FEM Optimization of Properties | Modeling of Loudspeakers | Measurement Verification



- Loudspeaker #1 from the beginning showed a good matching between measured and simulated results.
  - E_{Spider} was updated to 6 MPa, staying within it's displacement tolerance, matching measured resonance from from 59 Hz to 70 Hz.
  - Multiple Frequency Domain studies were performed, in any case, to consider the effects of changes in other parameters.

Cone: Paper + 15% Mica
Surround: Nitril Rubber 60A

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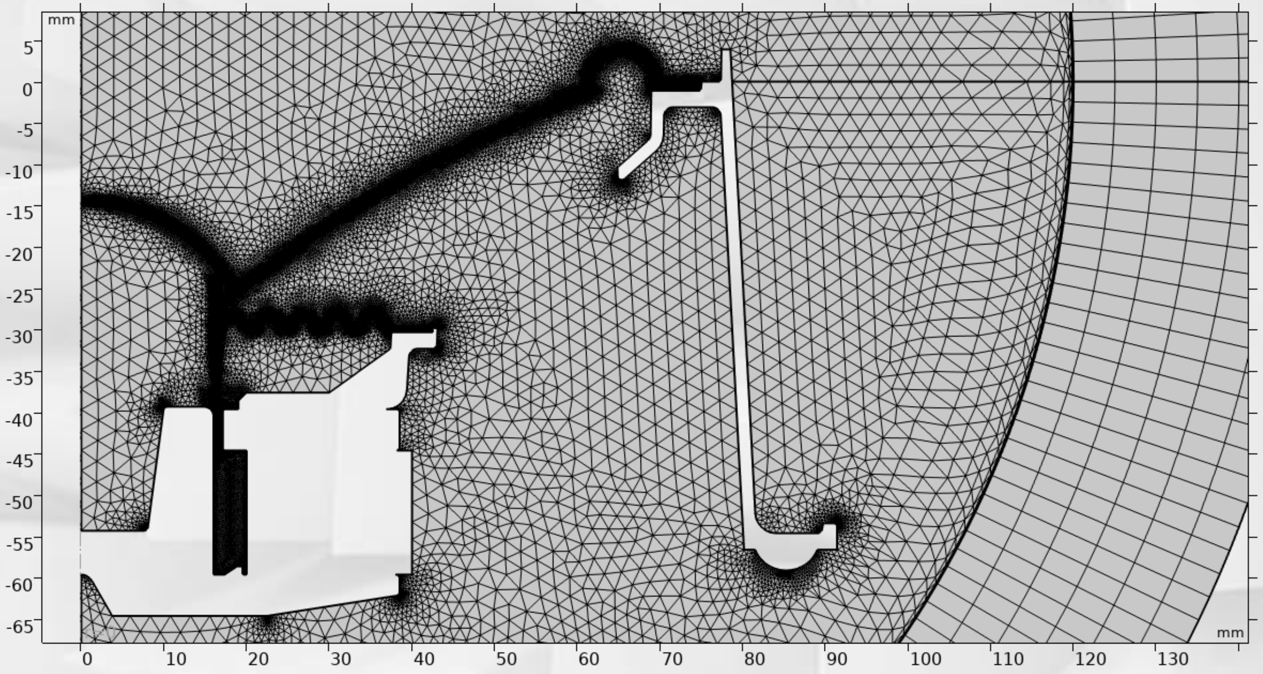
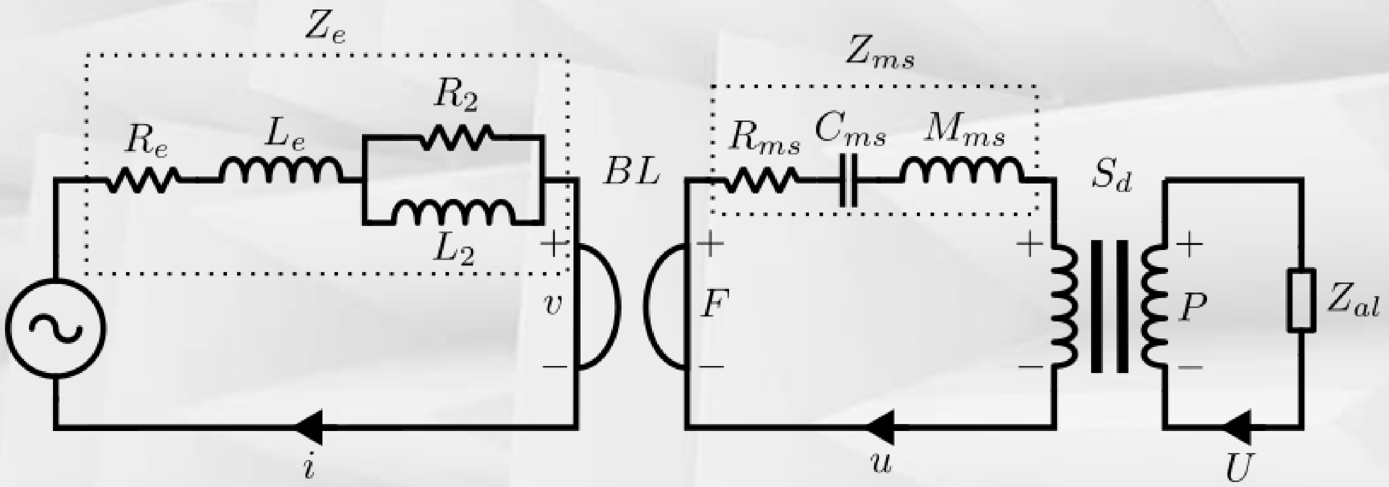
Loudspeaker FEM Models - Mesh

- The mesh is refined in regions with expected large velocity gradients
  - Moving components
  - Around voice coil where thermoviscous losses are expected
- Air domain mesh is configured to ensure a minimum number of elements present per smallest wavelength.



Electro-Mechanical-Acoustical (EMA) Analogies

- EMA is a way of describing loudspeakers behavior using simple circuits
- Klippel's model of the electrical domain
- Impedance analogy
- Thiele-Small (T/S) Parameters



Symbol	Description
R_e (Ω)	DC resistance of voice coil
L_e (mH)	Voice coil inductance
R_2 (Ω)	Eddy currents resistance
L_2 (mH)	Para-inductance, high frequencies
Bl (Tm)	Force factor
f_s (Hz)	Free air resonance frequency

Electrical Thiele-Small (T/S) Parameters

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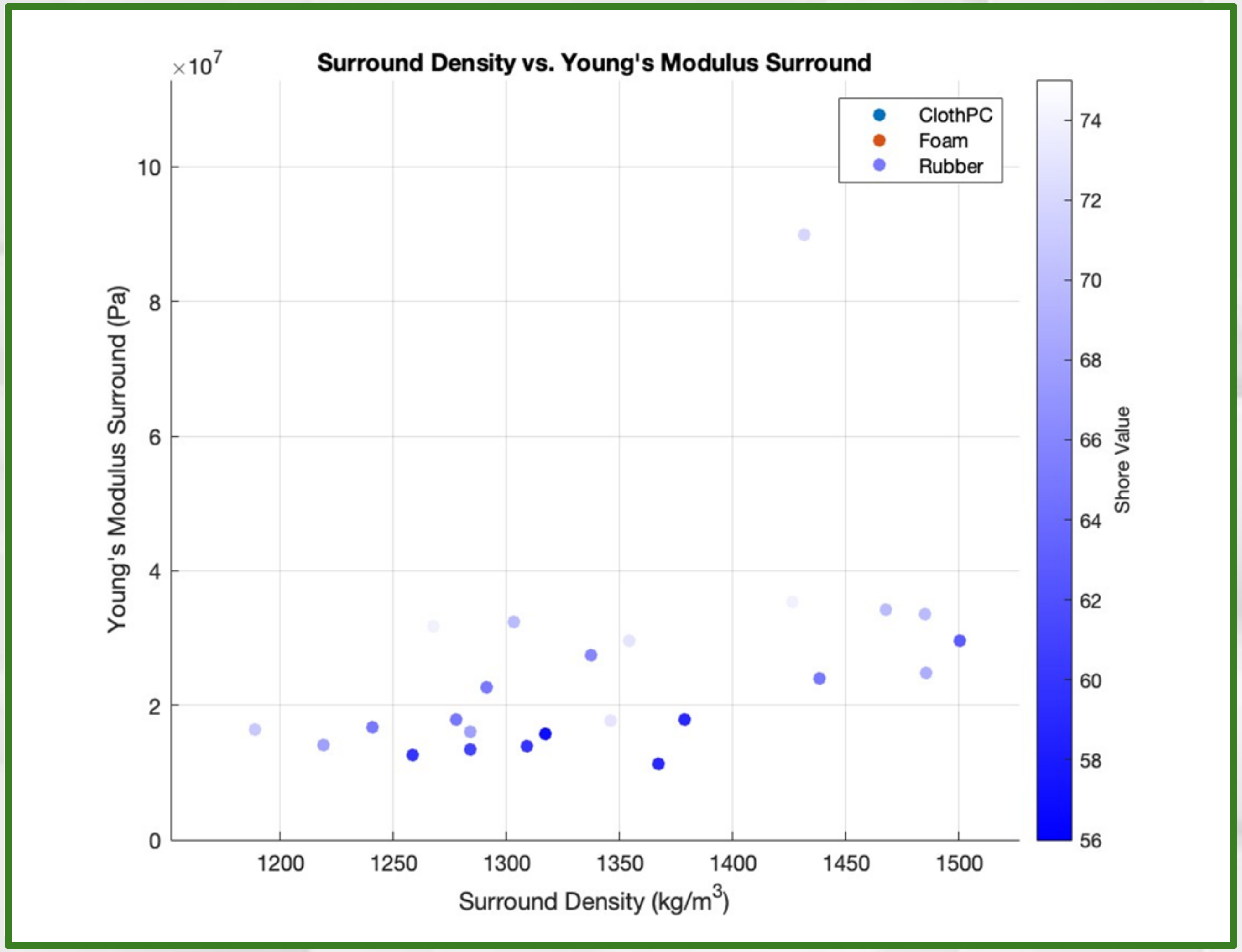
Results – Surround Materials

Analysis of Materials | FEM Optimization of Properties | Modeling of Loudspeakers | **Measurement Verification**



- Foam
  - Almost constant $E_{Surround}$ around 8 MPa
  - Slight variations in density
- Poly-Cotton Cloth
  - Increased $E_{Surround}$ with increase density
  - Very high variability: due to production processes, weaving patterns, or resins used.
- Rubber
  - High variation in density
    - (90% higher than foam surrounds)
  - Slight trend with increasing $E_{Surround}$ with increasing Shore, however more measurements are needed

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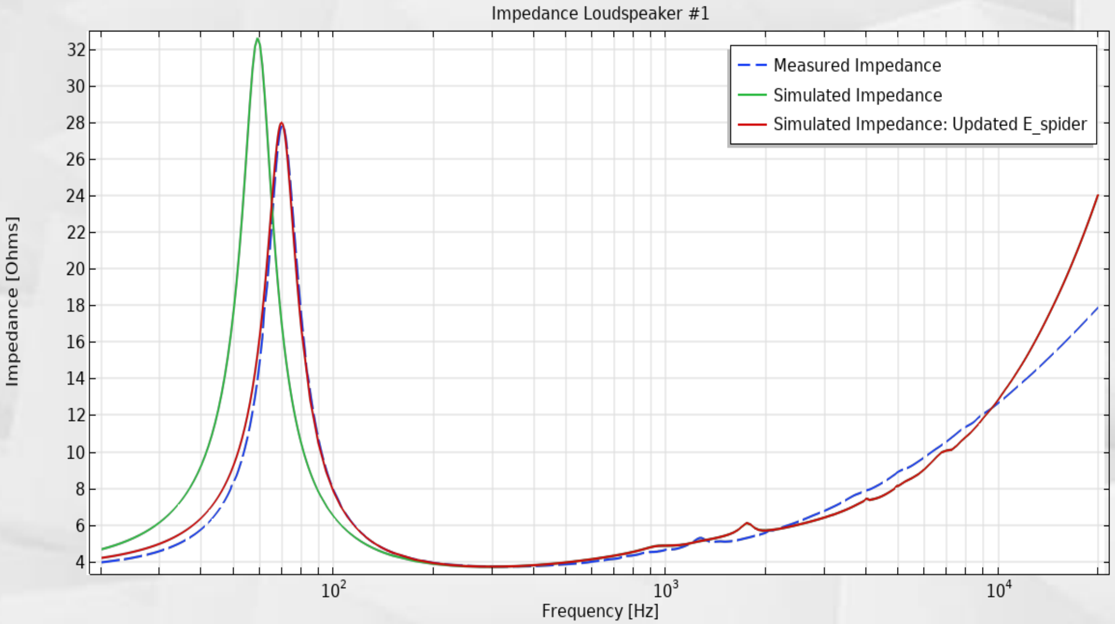
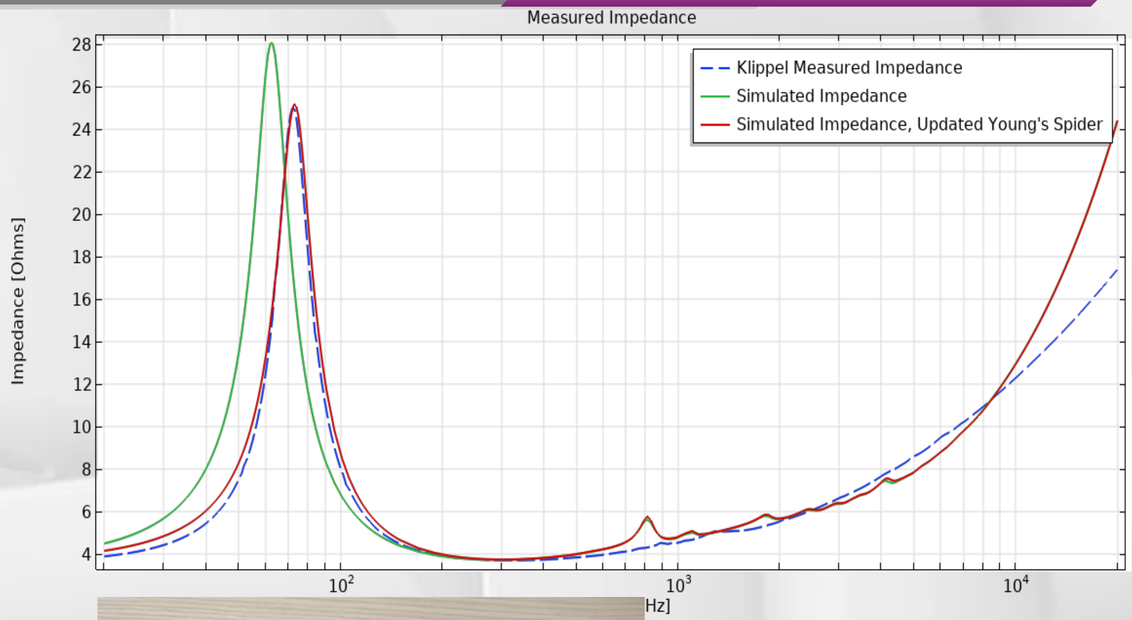
Results – Loudspeaker #1

Analysis of Materials → FEM Optimization of Properties → Modeling of Loudspeakers → **Measurement Verification**





Cone: Paper + 15% Mica
Surround: Nitril Rubber 60A

Cone: Fiberglass
Surround: Nitril Rubber 60A

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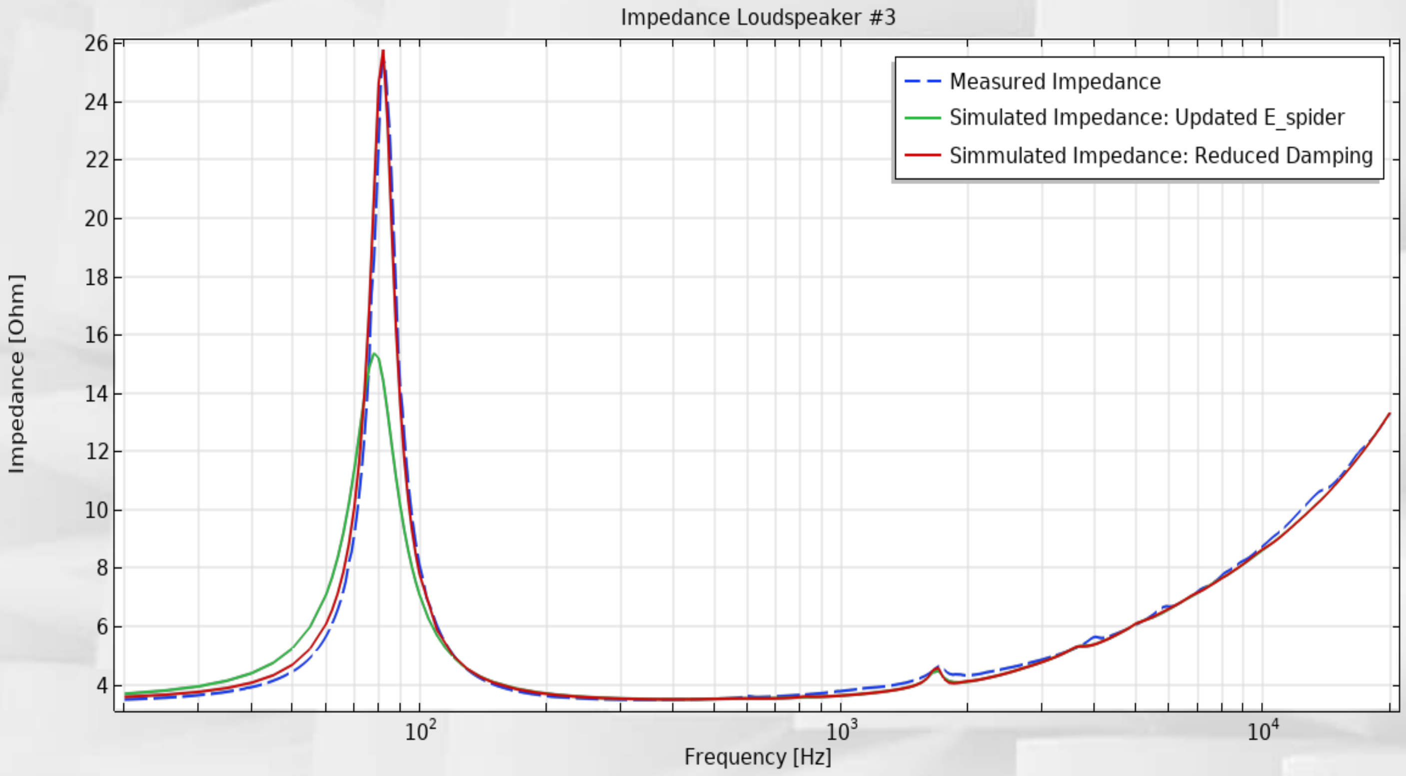
Results – Loudspeaker #1

Analysis of Materials → FEM Optimization of Properties → Modeling of Loudspeakers → **Measurement Verification**



Cone: Paper +10% Mica
Surround: Polyurethane Foam

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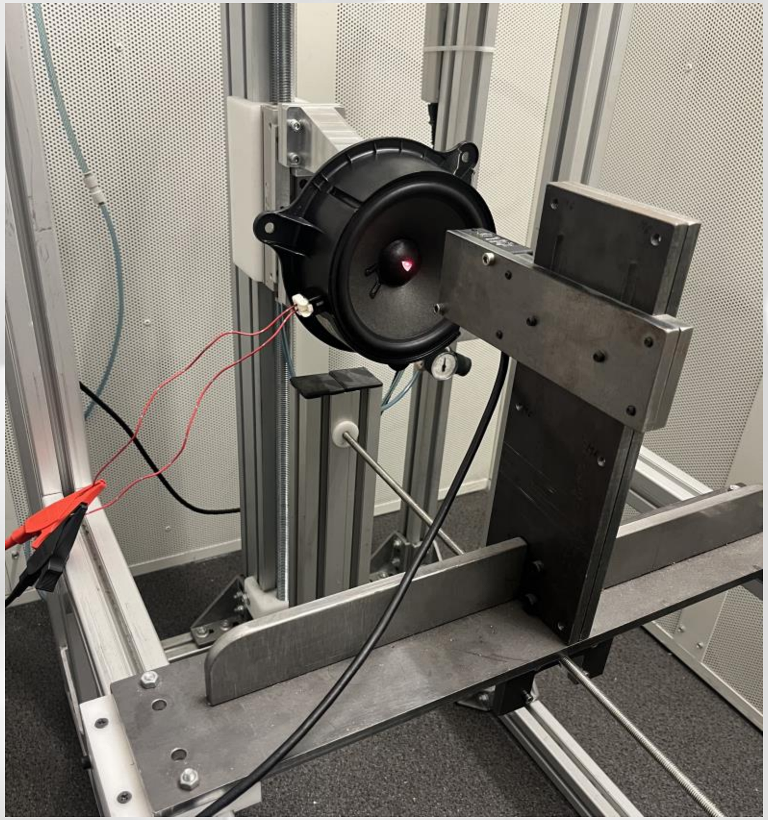
Klippel® Linear Parameter Measurement (LPM) Module

- Terminal voltage and current to derive electrical impedance while applying a sinusoidal sweep.
- Mechanical measurements taken using a laser displacement sensor.
- Based on a linear small-signal lumped-parameter model of the loudspeaker
- A fitting process is made by optimizing the model parameters
  - Minimize difference between measured impedance and the model impedance, to obtain the lumped model parameters.



Material Samples

- 35 Loudspeaker membranes analyzed ⌀96 to ⌀196 mm in diameter

Cone

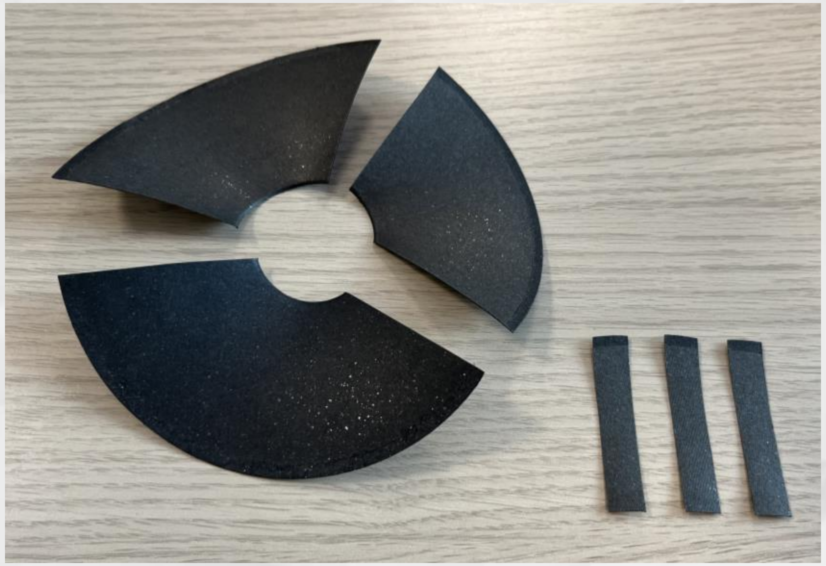
  - 31 Averaged resonance frequency measurements (3 strips from each membrane)
    - 9 Fiberglass
    - 7 Paper + mica powder
    - 4 Paper + Kevlar
    - 11 Paper filtered
  - 4 Measurements unable to consider, the test strips too short or too thick.

Surround

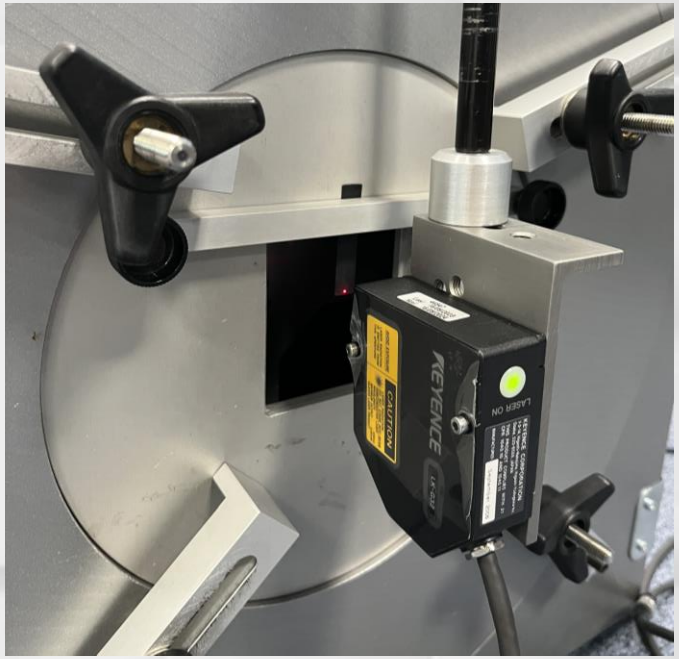
  - 34 Averaged resonance frequency measurements (3 membranes from the same manufacturer)
    - 25 Rubber
    - 4 Foam
    - 5 Cloth polycotton
  - 1 unable to consider, even with an added mass

Cone and Surround Material Measurements

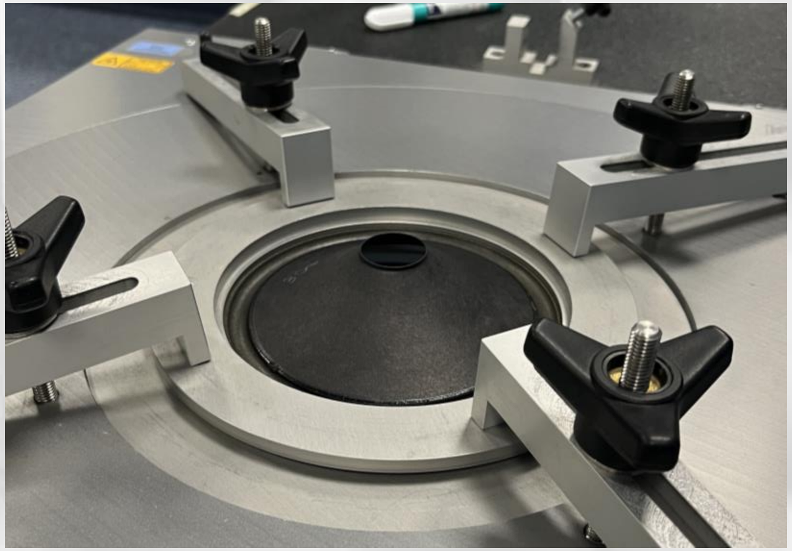
- For cone material measurements, standard MPM procedure was followed.
- MPM Input:
  - Length
  - Density
  - Thickness



Cone Material Testing:



Surround Material Testing:



Future Works

- Expand dataset and validate trends.
- Explore materials with unique properties.
- Characterize materials under various environmental conditions.
- Optimization algorithm in the FEM environment to automatically adjust material properties → more efficient evaluation of new designs.