Advancements in Acoustical Topology Optimization

René Christensen, CEO, PhD

COMSOL Conference Munich, October 2023

Company Presentation

Consultancy

- Research based product development
  - Computational Modeling
    - FEM/BEM
    - Analytical
    - Optimization

Training & students

- Engineering mathematics
- Vibroacoustics

CONTENT

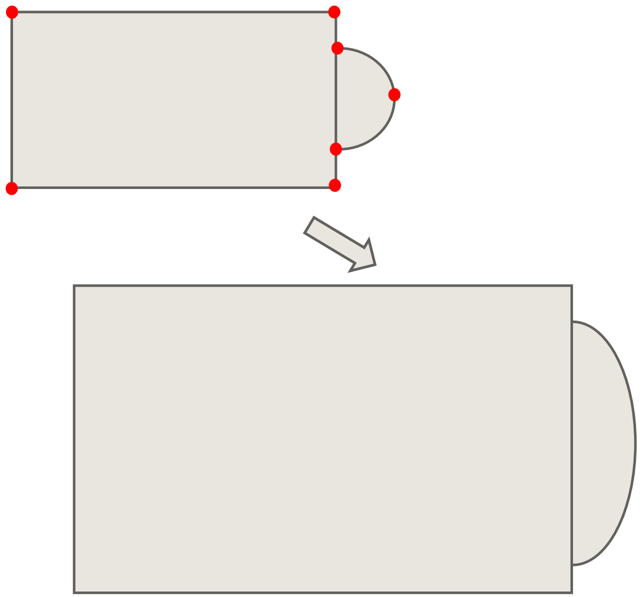
- LinkedIn
- Blog
- Audio Science Review
- audioXpress

www.acculution.com
info@acculution.com

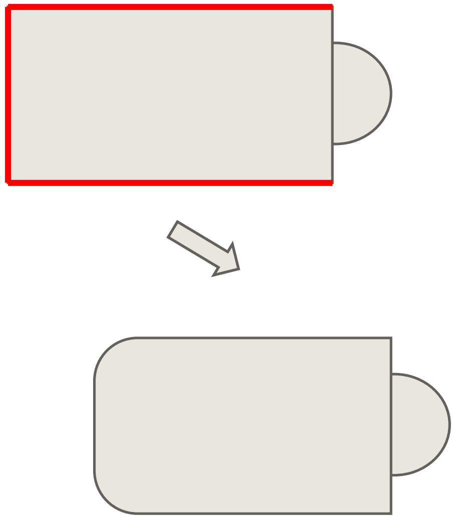
Table of Content

Geometry Optimization

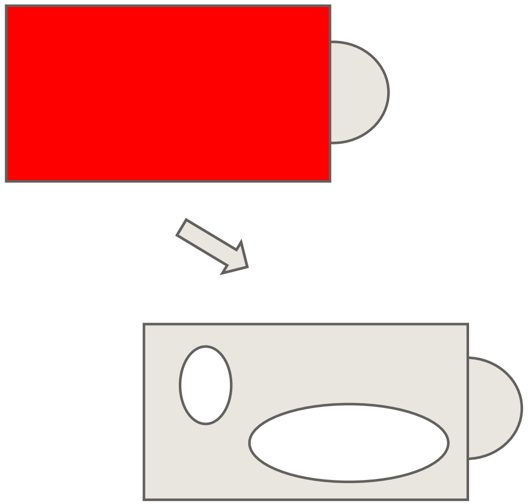
Parameter (size) Optimization



Shape Optimization

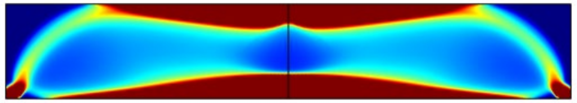


Topology Optimization



Topology Optimization

2015



2017

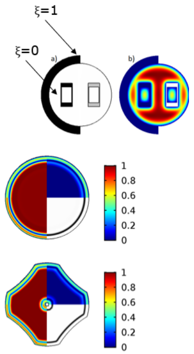
$$a_v(\xi)\Psi_v + k_v^{-2}\Delta_{cd}\Psi_v = f_v(\xi)$$

$a_v(\xi)$ and $f_v(\xi)$ are interpolated via e.g. SIMP or RAMP

$$a_h(\xi)\Psi_h + k_h^{-2}\Delta_{cd}\Psi_h = f_h(\xi)$$

$$\min_{\xi}: \Phi(\xi, \Psi_v, \Psi_h)$$

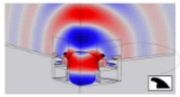
$$\text{s.t.}\begin{Bmatrix} 0 < \xi(x,y) \leq 1 \quad \forall\,(x,y) \in \Omega_{cd} \\ \int_{\Omega_{cd}} \xi d\Omega_{cd} \leq \beta\Omega_{cd} \end{Bmatrix}$$



$$\max_{\xi}: \Phi = \Re(R') = \omega\rho_0\Re\left(\frac{i}{\int_{\Omega_{cd}(\xi)} \boldsymbol{\Psi}_v d\Omega_{cd}}\right)$$

$$\text{s.t.}: \begin{cases} \mathbf{0 < \xi \leq 1} \\ \int_{\Omega_{cd}} \boldsymbol{\xi} d\Omega_{cd} / \Omega_{cd} \leq \beta \\ \mathbf{S_\phi \Psi_\phi = f_\phi} \end{cases}$$

2019



Acoustic Topology Optimization – Implementation and Examples

R. Christensen[1]
[1]GN Hearing A/S, Denmark

Introduction In recent years there has been a focus on using topology optimization in the field of acoustics [1,2], whereas previously the technique has been applied mostly within structural mechanics, thermodynamics, and fluid dynamics [3]. This paper describes the mathematical basis … *read more*

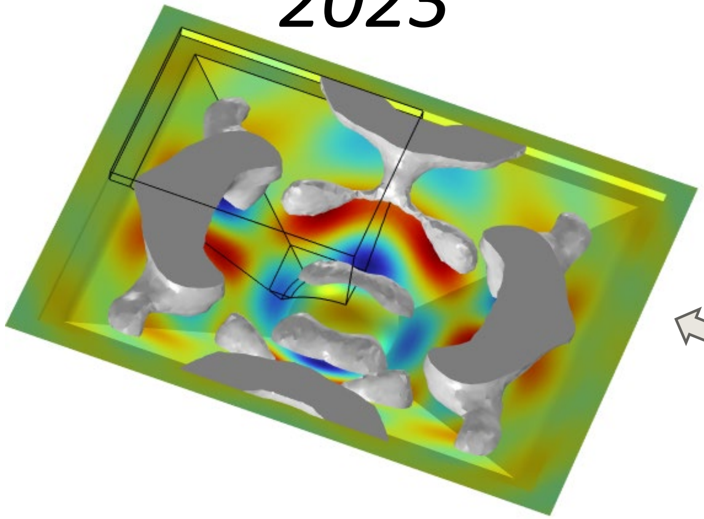
2020

Shape and Topology Optimization of Loudspeaker Drivers

R. Christensen[1]
[1]GN ReSound A/S, Lautrupbjerg 7, DK-2750 Ballerup, Denmark

Shape and Topology Optimization of Loudspeaker Drivers This paper illustrates the use of formal mathematical optimization techniques for engineering solutions focused towards loudspeaker drivers. Both shape and topology optimization techniques are applied, with the physics ranging … *read more*

2023



Topology Optimization

- Design domain

$$\xi \,, u(\xi)$$

- Design variables

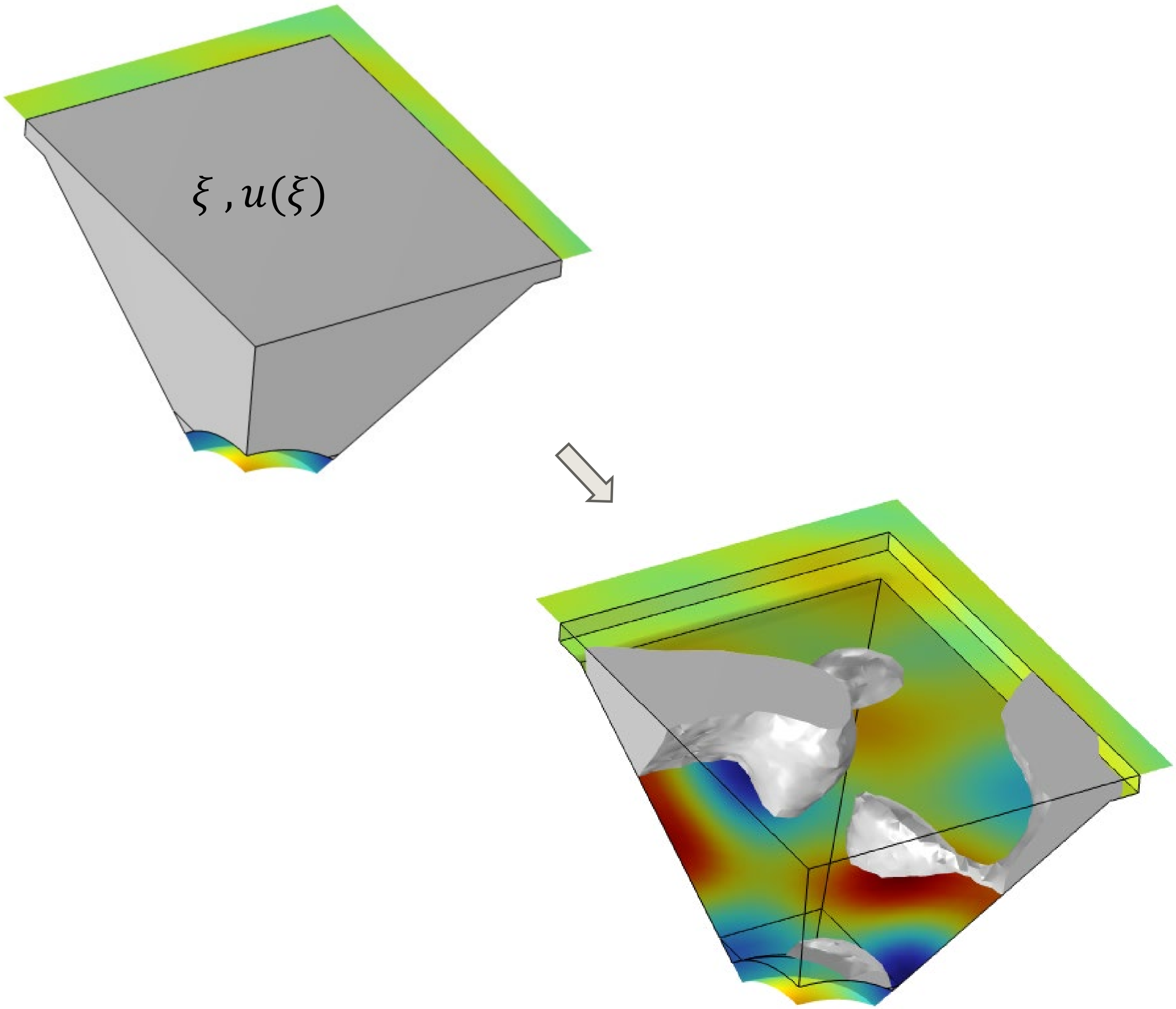
$$0 \leq \xi(\boldsymbol{x}) < 1 \qquad \forall \boldsymbol{x} \in \Omega_{\mathrm{d}}$$

- Objective function

$$\min_{\xi} \Phi(\xi, u)$$

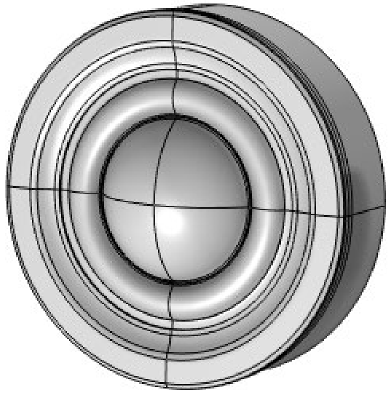
- Constraints

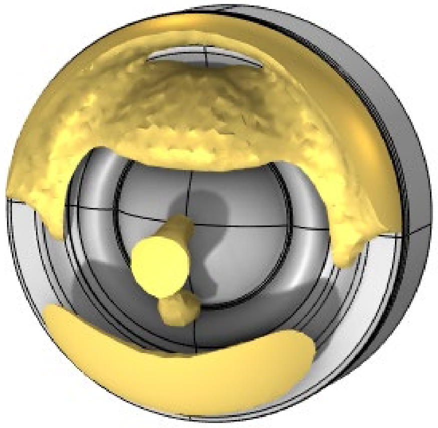
$$g_{\mathrm{j}}(\xi, u) \geq 0, j = 1,2, \dots, J$$
$$\mathrm{h}_k(\xi, u) = 0, k = 1,2, \dots, K$$

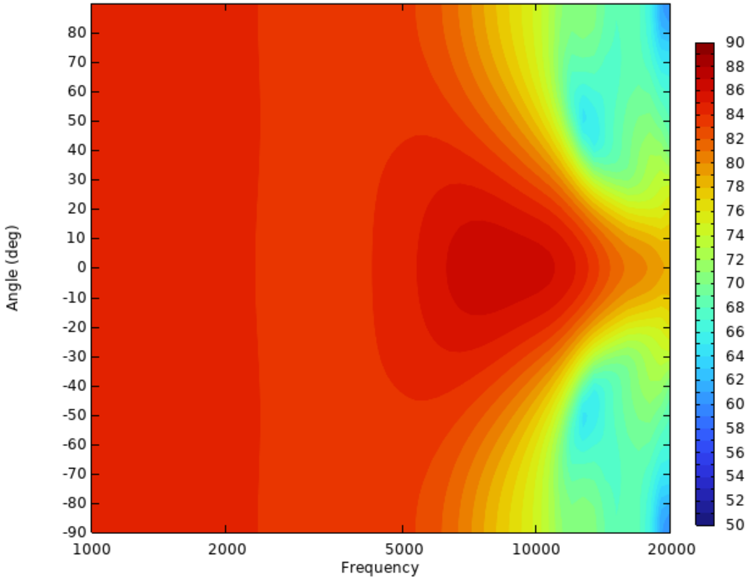


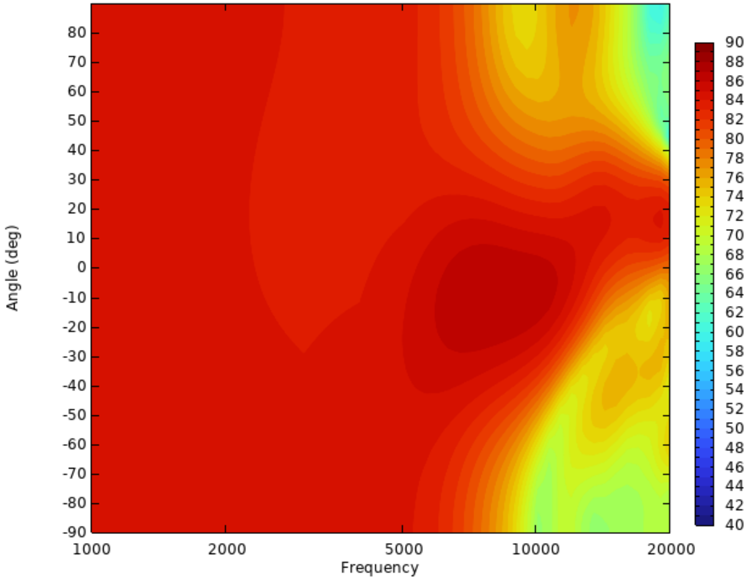
Topology Optimization

Tweeter Example





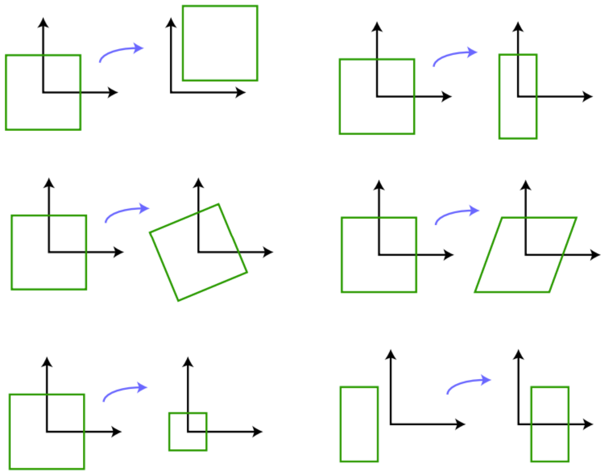




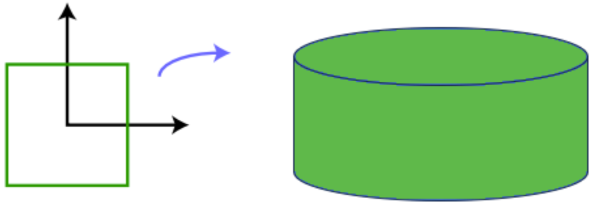
Auxiliary Constraints

Used for **aesthetics** requirements, to control **directivity**, **reduce computational load,** and to **overcome software limitations.**

Affine Constraints



General Constraints



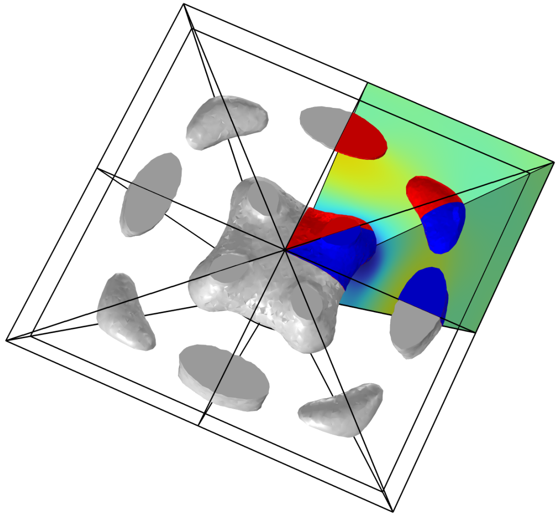
Equation-based Constraints

$$\boldsymbol{p}(P) = \frac{-\omega^2\rho}{2\pi}\int_S \boldsymbol{w}(Q)\frac{e^{-ikR}}{R}dS$$

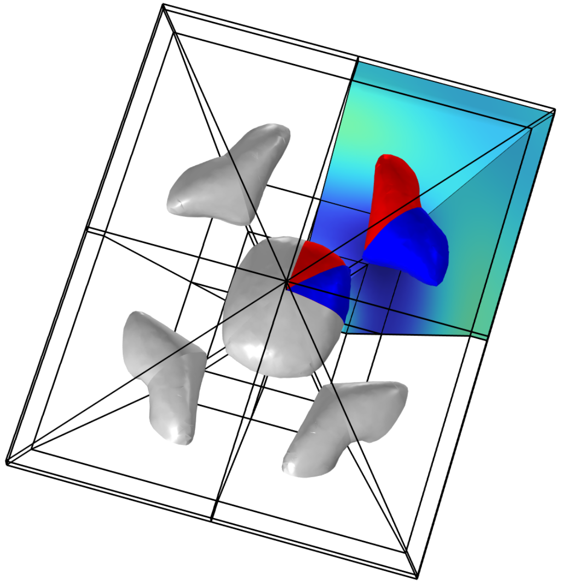
Auxiliary Constraints

Affine Constraints

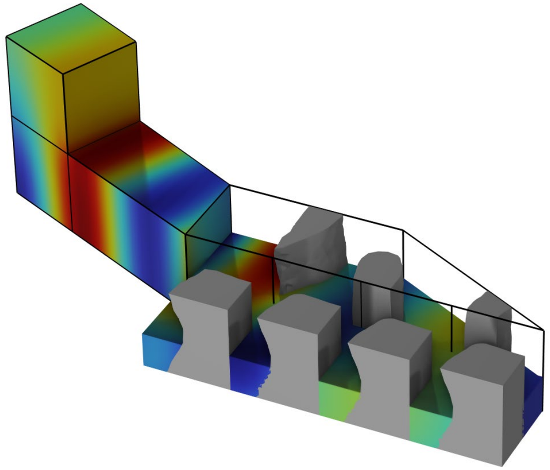
Mirror reflection



Nonuniform scaling



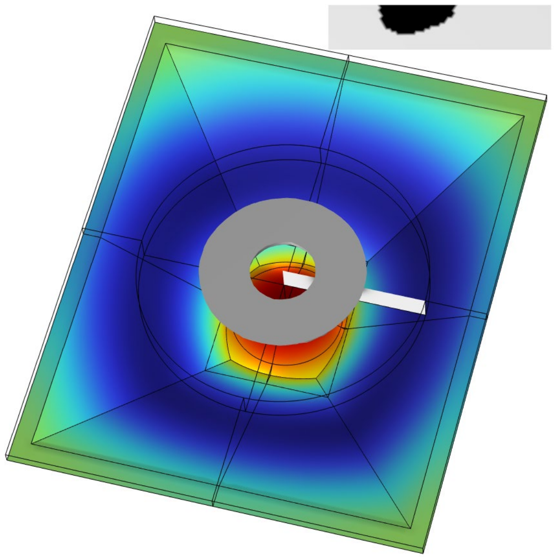
Repeating patterns

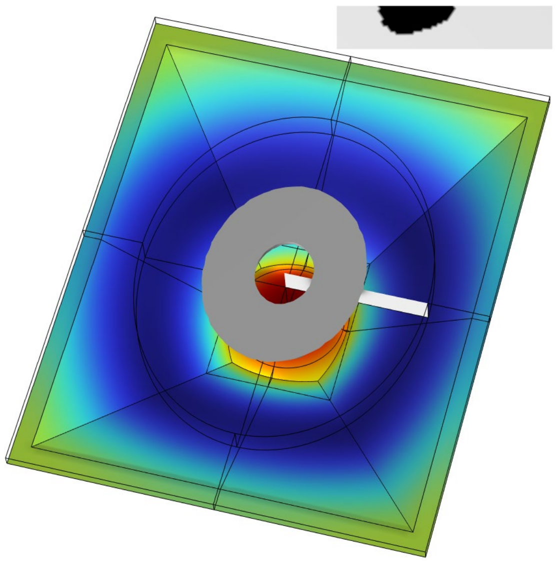


Auxiliary Constraints

General Constraints

2D Optimization/3D Physics for Path Extrusion Constraint





Auxiliary Constraints

Equation-based Constraints

Overcome software limitations; Kirchhoff-Helmholtz Equation modification

Exterior Field Calculation; XY, YZ, or XZ limitation

The exterior field operator and its associated variables are optimized for use in postprocessing. They cannot be used for gradient based optimization studies, like shape and topology optimization, where the sensitivity is necessary.

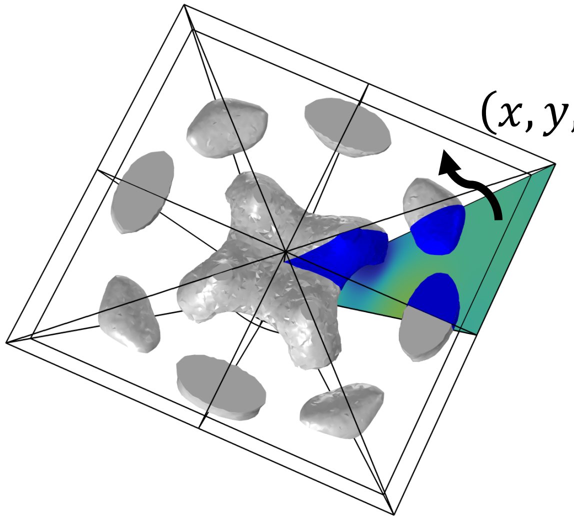
For gradient based optimization a dedicated operator exists in 3D for the pressure `pext_opt(x,y,z)` and for the sound pressure level `Lp_pext_opt(x,y,z)`. These two operators can be used to define objective functions, like specifying a target spatial response. The operator only exists when the **Symmetry type** option is set to **Symmetry planes** (the default), this is in particular true when all symmetry planes are set to **Off**.

An example is given in the *Shape Optimization of a Rectangular Loudspeaker Horn in 3D* tutorial. Application Library path **Acoustics_Module/Optimization/rectangular_horn_shape_optimization**

But…

$$4\pi p(P) = \int_S p(Q)\frac{\partial G(P,Q)}{\partial n} - G(P,Q)\frac{\partial p(Q)}{\partial n}dS$$

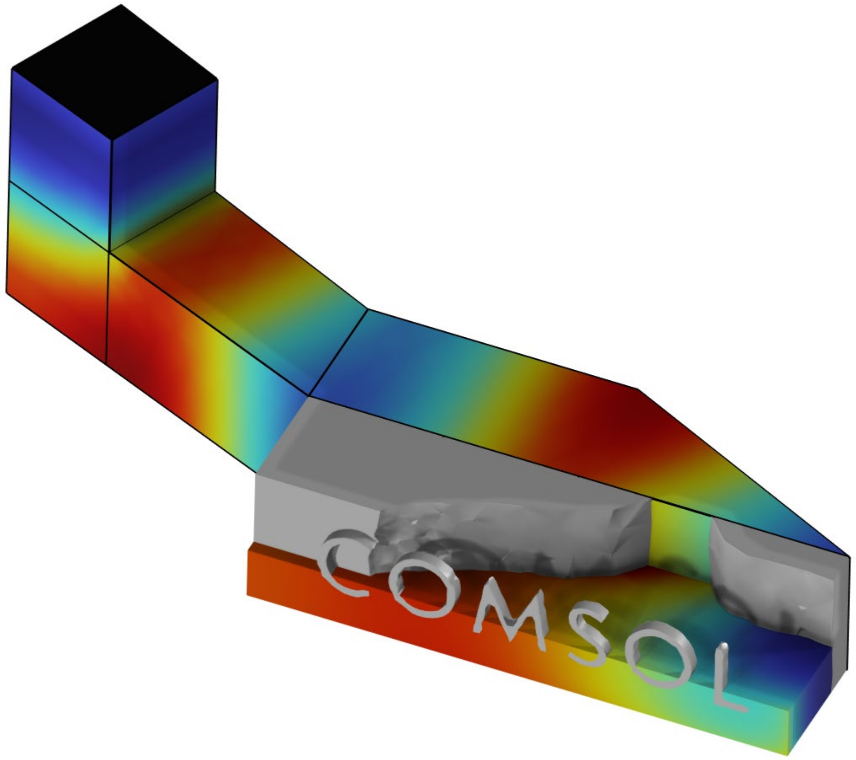
$$4\pi p(P) = \int_{S_1} I_1(x,y,z)dS_1 + \int_{S_1} I_2(x',y',z')dS_1$$

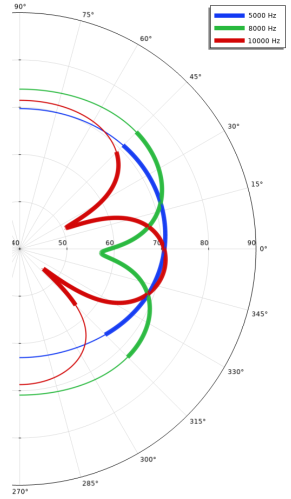


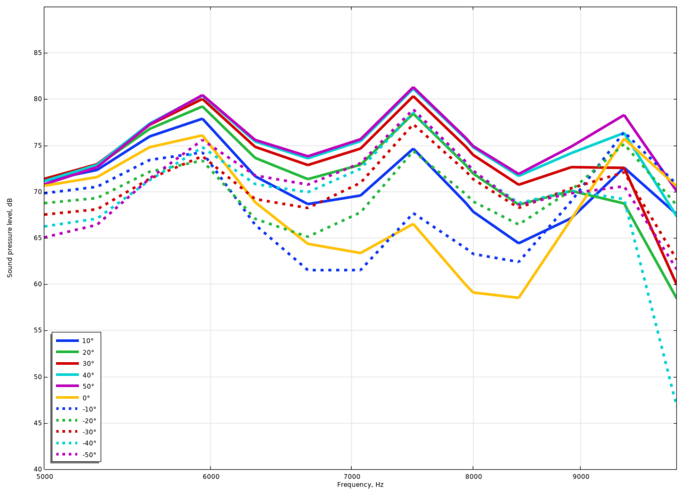
$(x,y,z) \rightarrow (x',y',z')$

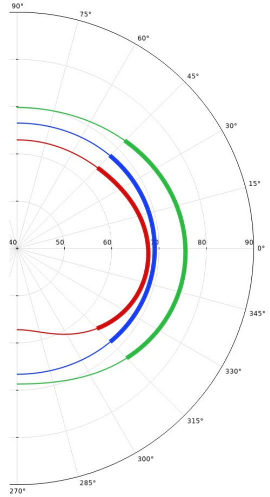
Topology Optimization

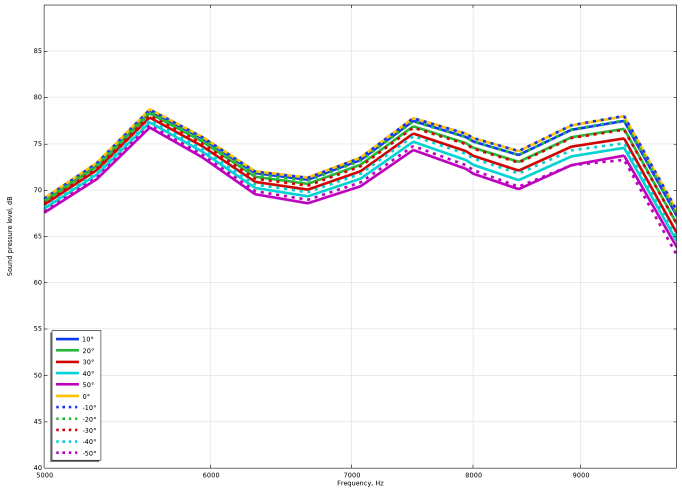
Waveguide Example











Conclusion

- **Topology Optimization** can lead to innovative and non-intuitive engineering solutions

- **Auxiliary Constraints** add further design requirements relevant for industry cases.

- **Solutions are now out in the Audio Industry!**