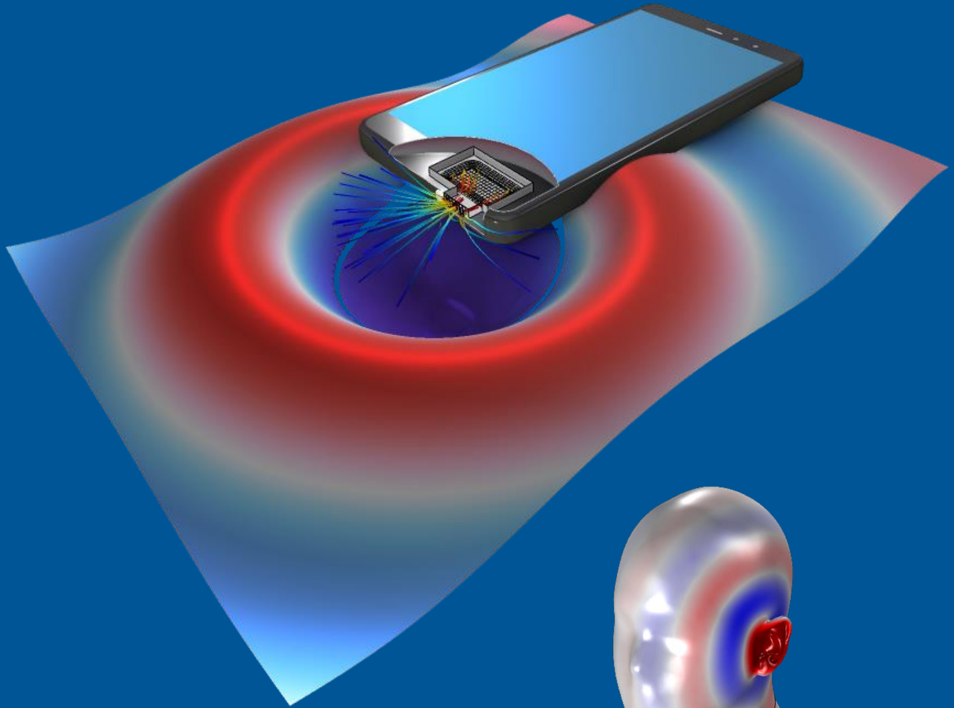
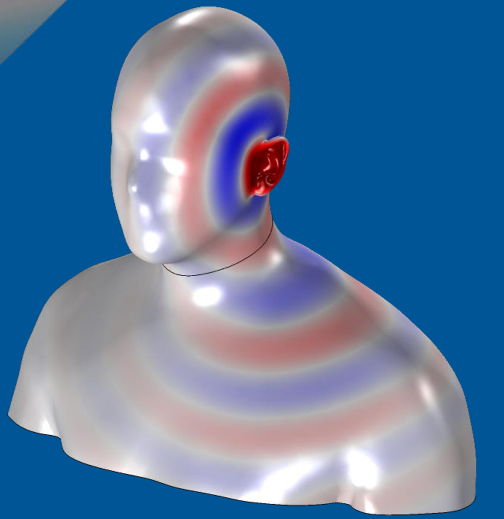
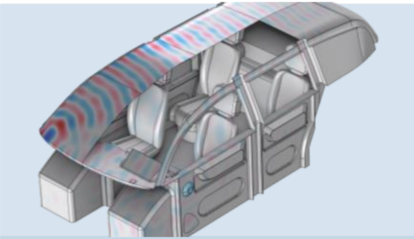




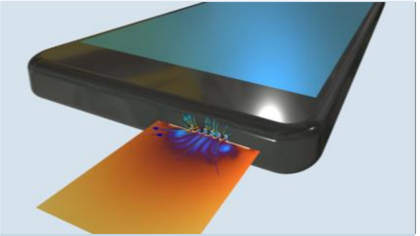
Acoustics Module

The Acoustics Module



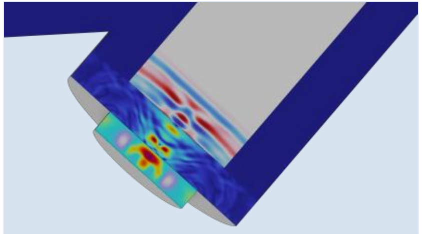
Pressure Acoustics

Classical acoustics, attenuation, porous media models, with a variety of modeling formulations



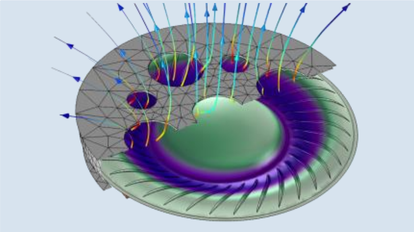
Thermoviscous Acoustics

Microacoustics, microtransducers, MEMS, thermal and viscous boundary layer losses, etc.



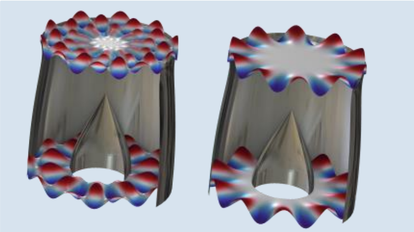
Elastic Waves

Elastic waves in solids; mixed pressure and elastic waves in porous materials



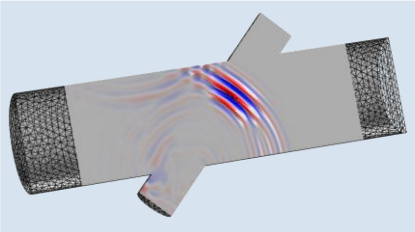
Acoustic–Structure Interaction

Full vibroacoustics analysis with easy and intuitive built-in multiphysics couplings



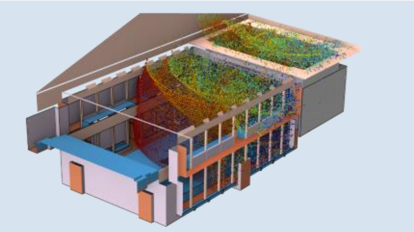
Aeroacoustics

Convected acoustics, Linearized Navier–Stokes and Linearized Euler formulations, convected wave equation, flow-induced noise, and mode extraction



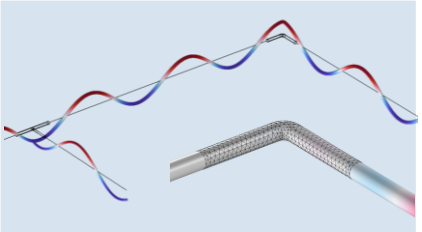
Ultrasound

Ultrasound propagation, piezoelectric transducers, linear and nonlinear



Geometrical Acoustics

High-frequency methods using ray tracing for room acoustics and more; full wave to ray couplings



Pipe Acoustics

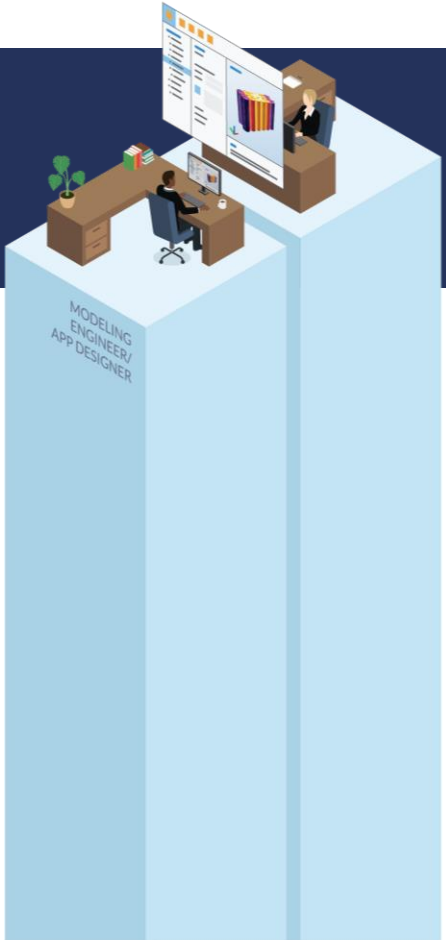
Wave propagation in 1D pipe structures with background flow effects; 1D to 3D coupling for system simulation

COMSOL

COMSOL Multiphysics®
Version 6.0

A new paradigm in multiphysics modeling

- To provide an all-encompassing workspace or modeling environment of the product design workflow
- Equation-based modeling



Model Builder

Supports all facets of the modeling process

- Platform feature utilizing physics interfaces
  - Creates a framework for extendable modeling — *multiphysics*
  - Add-on modules

Model Builder

Graphics

Switch between the Model Builder, Application Builder, and Model Manager

Geometry

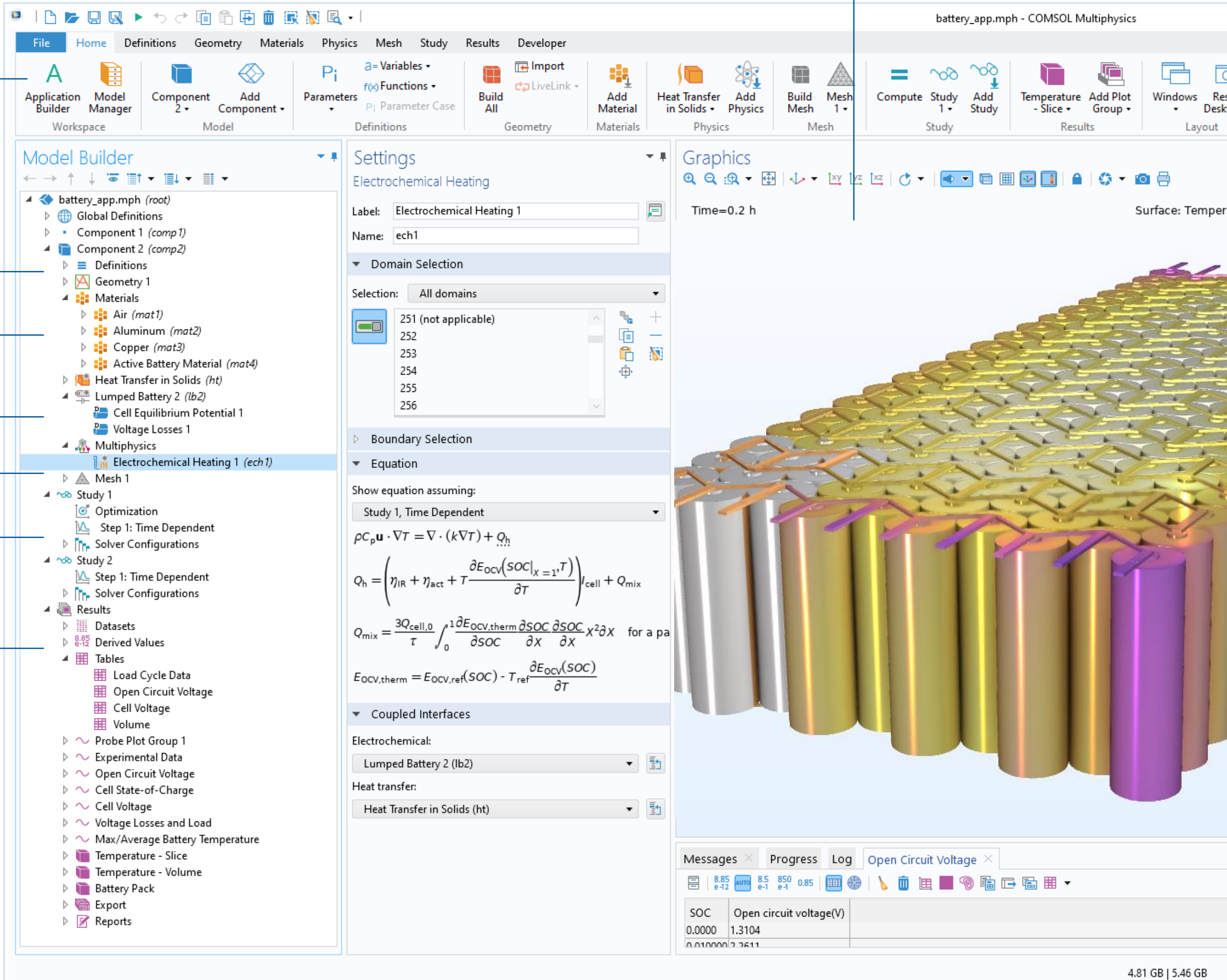
Materials

Physics

Mesh

Studies

Results



Application Builder

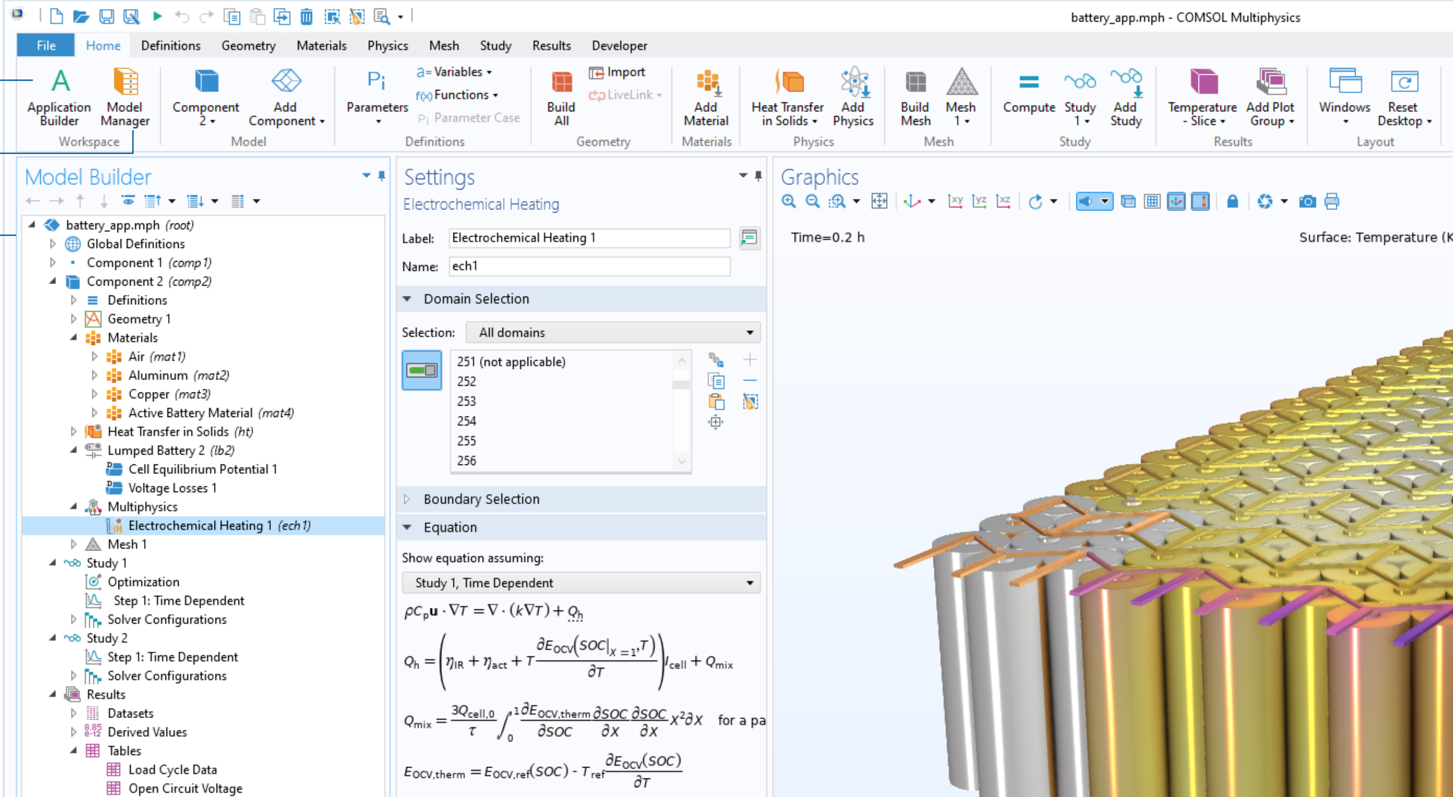
Supports extending modeling to specific engineering and technical applications

- Intuitive and flexible app development environment
- Collaborative, enhanced by the Model Manager

COMSOL

Application Builder

Go between:
Model Builder
Application Builder
Model Manager

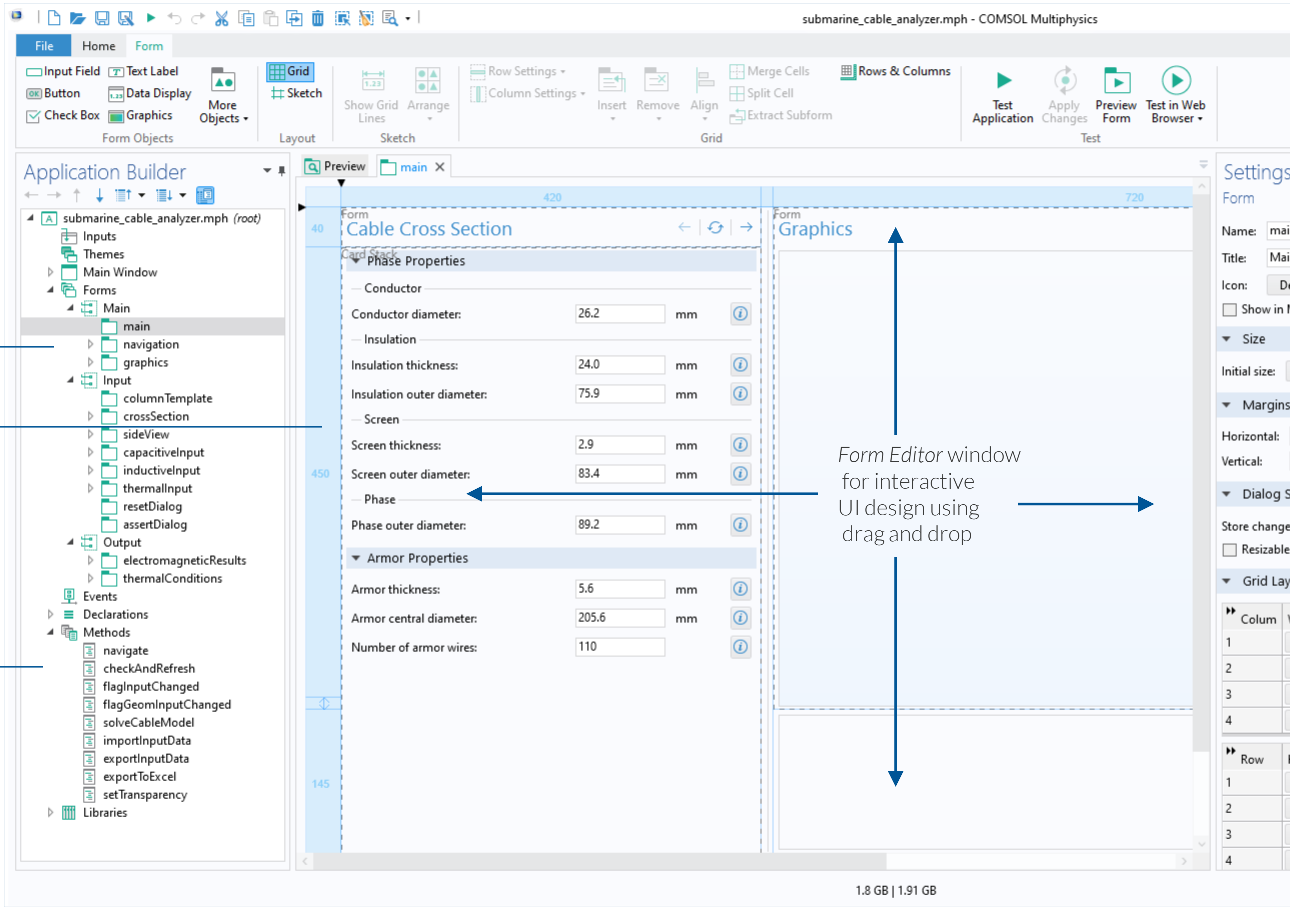


Application Builder

Forms and UI widgets

Access model parameters and settings

Methods to create code snippets in Java®



Simulation Apps

Provide data, such as designs, material data, and instructions

- Wide deployment options allowing broad usage by design engineers, operators, and technicians
- App results data informs manufacturing parameters

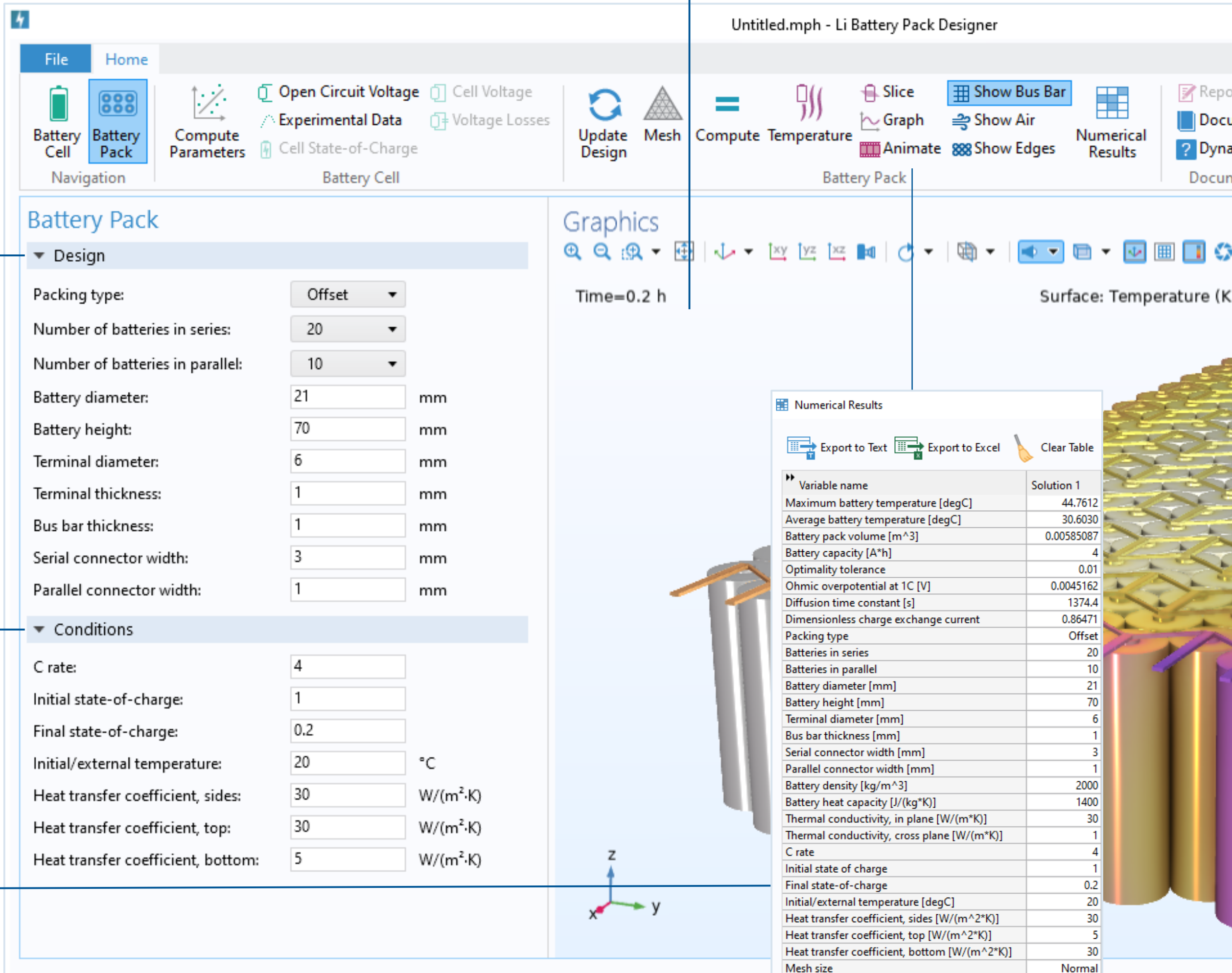
Simulation Applications

Graphics

Design

Operating conditions

Results



Model Manager

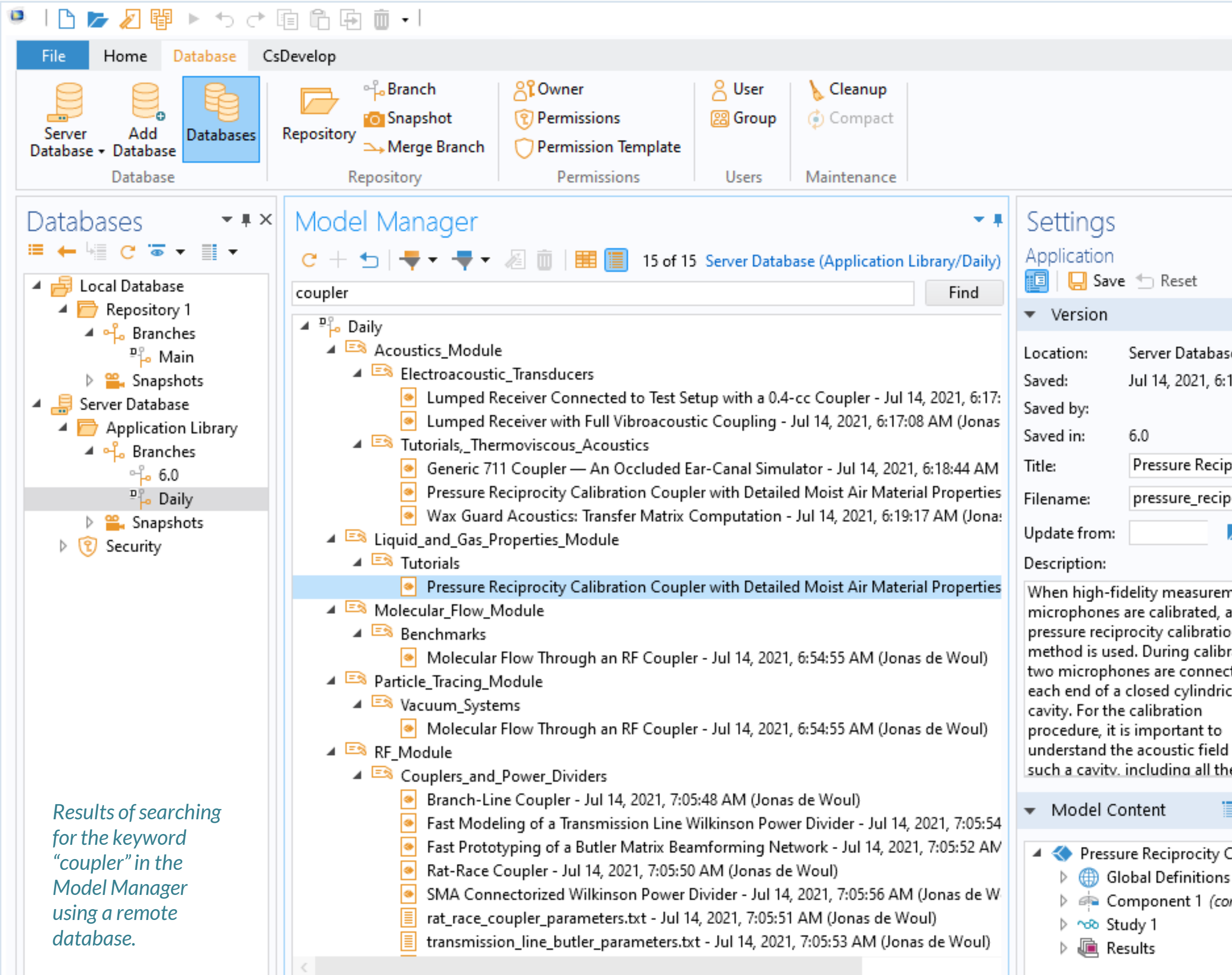
Democratization of simulation

- Collaborative and data-informed modeling process
- Resulting simulations accessible to all levels, at any stage of the product design life cycle

COMSOL

Model Manager

- Included in COMSOL Multiphysics
- Simulation data management
- Version control
- Efficient storage
- Searching model contents
- Access control
- Local or remote database



Results of searching for the keyword "coupler" in the Model Manager using a remote database.

The Acoustics Module - Is It Really “Multi”?

$$\nabla \cdot \left(-\frac{1}{\rho_c}(\nabla p_t - \mathbf{q}_d)\right) - \frac{k_{eq}^2 p_t}{\rho_c} = Q_m$$

$$\frac{1}{\rho c^2}\frac{\partial p_t}{\partial t} + \nabla \cdot \left[\left(1 + \frac{\beta p_t}{\rho c^2}\right)\mathbf{u}_t\right] = Q_m$$

$$\rho\frac{\partial \mathbf{u}_t}{\partial t} + \nabla \cdot (p_t \mathbf{I}) = \mathbf{q}_d$$

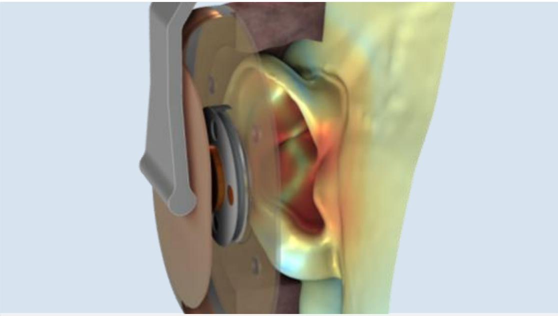
$$i\omega p_t + \nabla \cdot (\rho_0 \mathbf{u}_t) = 0 \qquad \beta = 1 + \frac{B}{2A}$$

$$i\omega \rho_0 \mathbf{u}_t = \nabla \cdot \boldsymbol{\sigma}$$

$$\rho_0 C_p(i\omega T_t + \mathbf{u}_t \cdot \nabla T_0) - \alpha_p T_0(i\omega p_t + \mathbf{u}_t \cdot \nabla p_0) = \nabla \cdot (k\nabla T_t) + Q$$

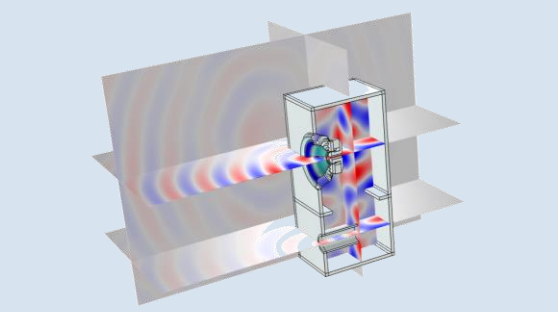
Multiformulation

- Helmholtz and wave equations
- Thermoviscous acoustics
- Linearized Navier–Stokes formulation
- Linearized Euler formulation
- Optimization
- Moving mesh and frames



Multiphysics

- Vibroacoustics (acoustic–structure)
- Piezoelectric materials
- Porous materials (Biot’s equations)
- Aeroacoustics (convected acoustics)
- Electroacoustics (fully coupled or lumped)



Multimethod

- Finite element method (FEM)
- Boundary element method (BEM)
- High-frequency BEM (HFBEM)
- Hybrid FEM–BEM modeling
- Ray tracing
- Discontinuous Galerkin (dG-FEM), time explicit

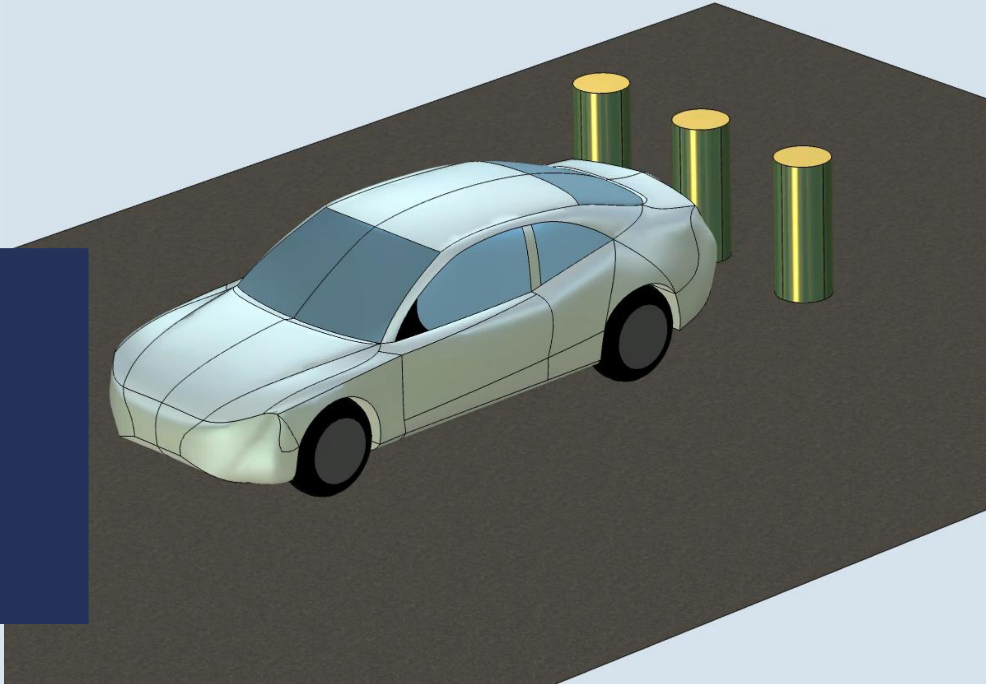
Ultrasonic Car Parking Sensor

Multiphysics

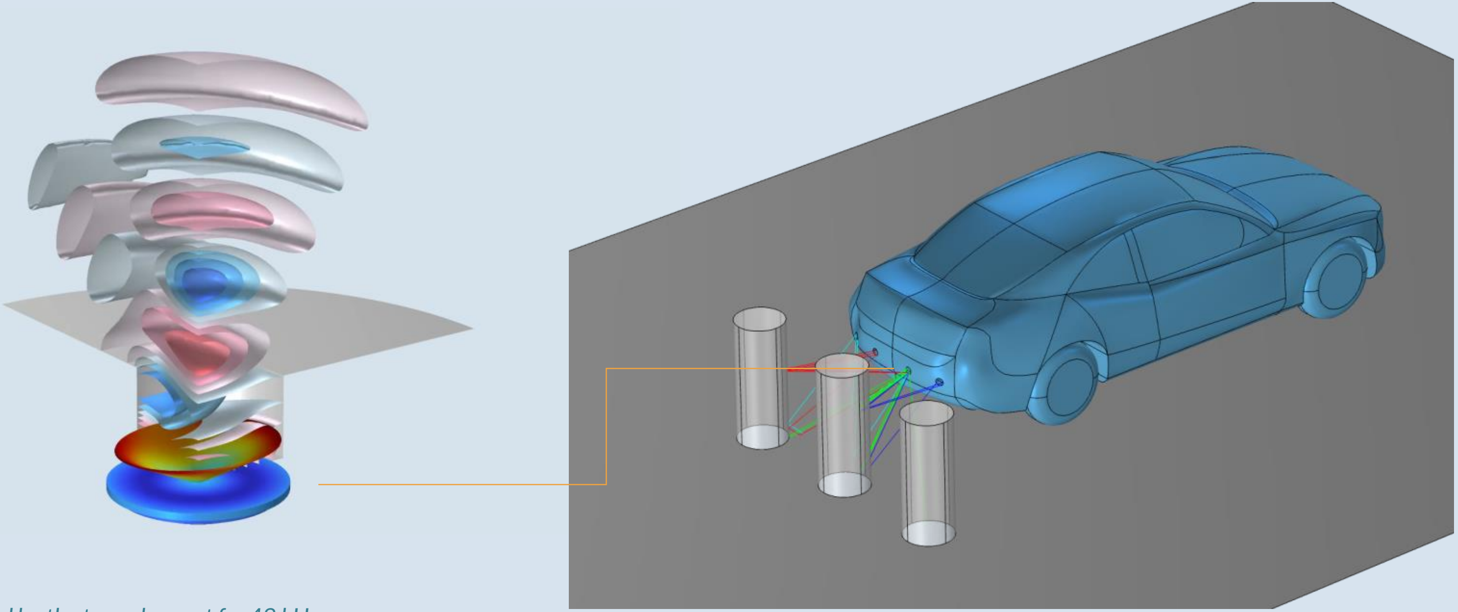
- Piezoelectricity
- Acoustic–structure interaction

Multimethod

- Finite elements
- Ray tracing

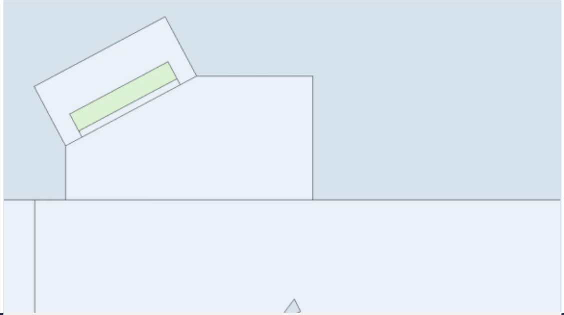


Ultrasonic Car Parking Sensor



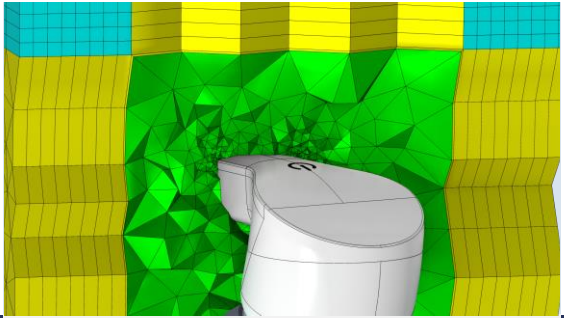
Acoustic pressure generated by the transducer at f = 48 kHz.

The Latest News (COMSOL Multiphysics® Version 6.0)



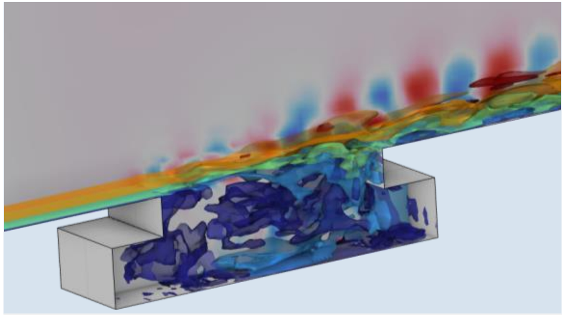
Piezoelectric Waves, Time Explicit

- Ultrasonic piezo transducers
- Multiphysics
- Time explicit higher-order formulation
- Hybrid FEM–dG method



Physics-Controlled Mesh

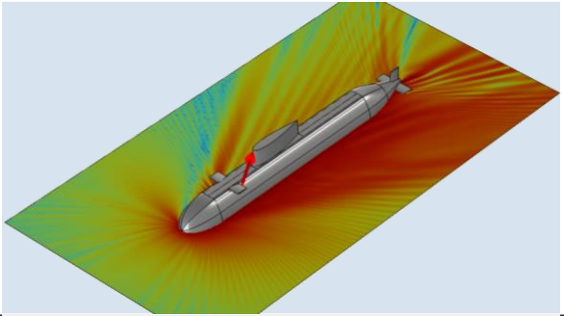
- Automated best-practices-based meshing
- Physics and material parameters analyzed



Introducing Flow-Induced Noise

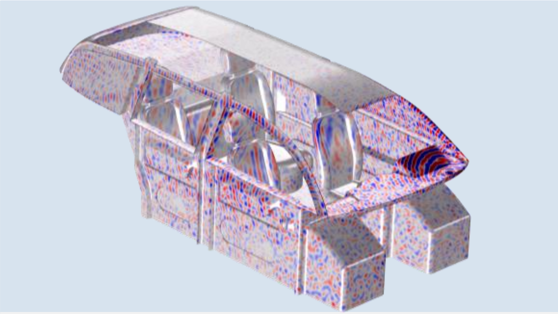
- Lighthill's acoustic analogy
- Acoustic wave equation (AWE)
- Multiphysics coupling and transient mapping

The Latest News (COMSOL Multiphysics® Version 6.0)



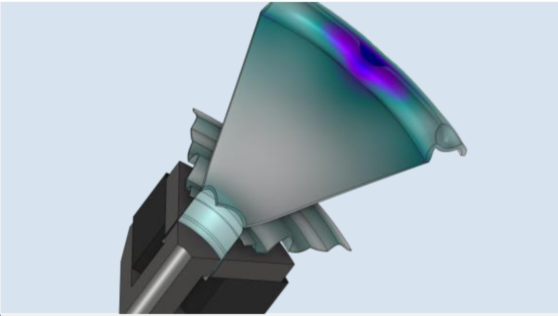
High-Frequency BEM

- Solve scattering and radiation problems efficiently
- Acoustically large problems



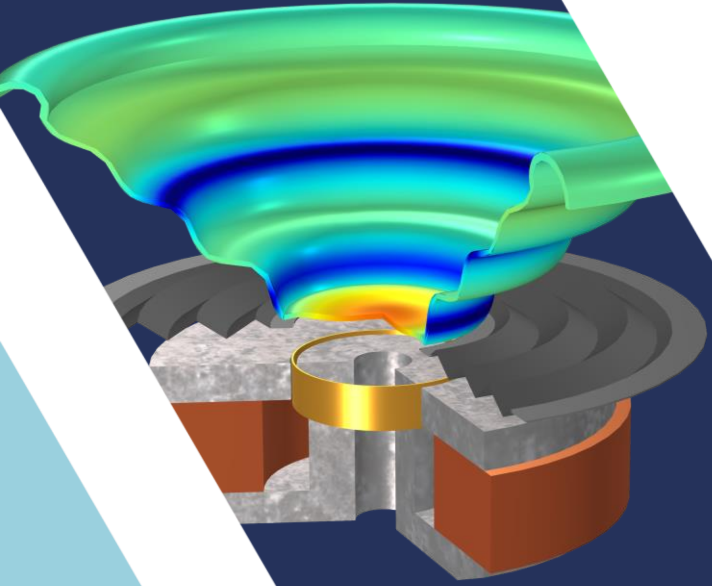
Performance

- Improved performance for solving large problems
- Improved automatic iterative solver suggestions



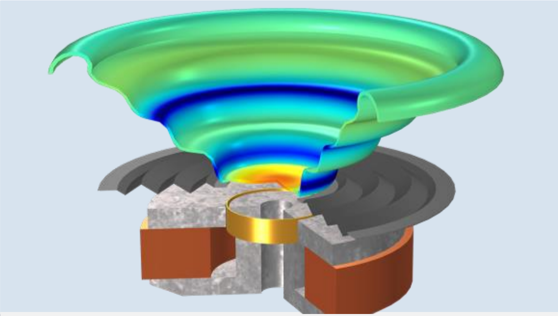
Optimization

- Dedicated functionality for acoustic optimization
- Improved handling for fixed driver mounts (rotation, scaling, and translation)



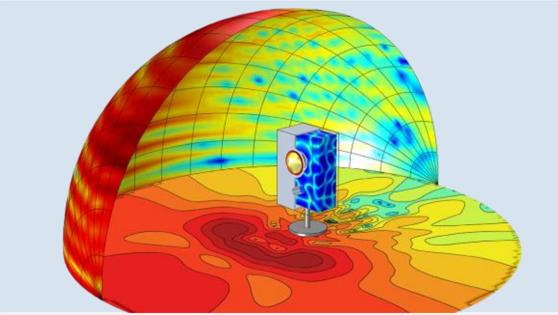
Loudspeakers

Analyses for Different Stages of the Development Cycle



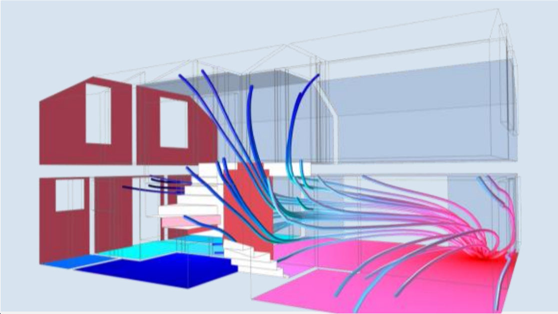
Speaker Driver Design

- Vibroelectroacoustic analysis: *Magnetic Fields; Pressure Acoustics, Frequency Domain;* and *Solid Mechanics* in the frequency domain, all fully coupled
- Nonlinear distortion: full transient study with moving mesh



Waveguide and Cabinet Design

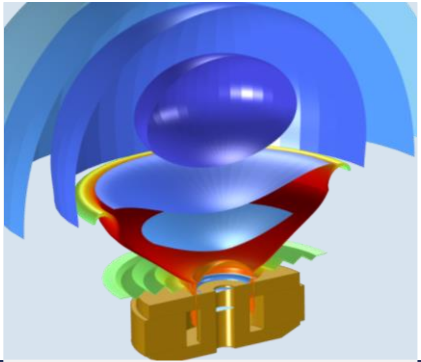
- Vibroacoustic analysis: *Pressure Acoustics, Frequency Domain* for the cabinet; *Pressure Acoustics, Boundary Elements* for the surrounding space; *Solid Mechanics* and *Shell* for the speaker components
- Frequency domain and eigenfrequency studies



Room Acoustics

- *Pressure Acoustics, Frequency Domain* for lower frequencies
- Two *Geometrical Acoustics* interfaces:
  - *Ray Acoustics* interface with a ray tracing study
  - *Acoustic Diffusion Equation* interface with an eigenvalue, stationary, or time-dependent study

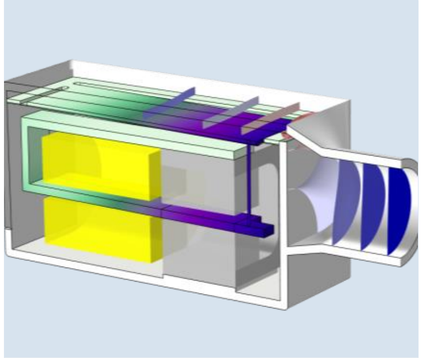
Multiphysics Couplings for Different Types of Speaker Drivers



Dynamic Moving Coil Transducers

Lorentz coupling

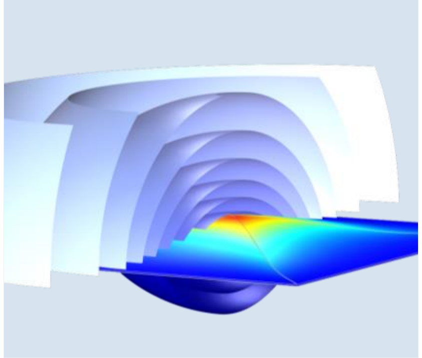
- *Magnetic Fields*
- *Solid Mechanics*



Balanced Armature Receivers

Magnetomechanical forces

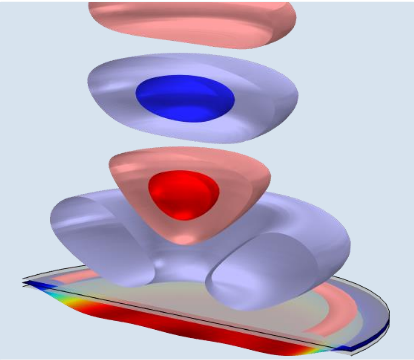
- *Magnetic Fields*
- *Solid Mechanics*



Piezoelectric Drivers

Piezoelectric effects

- *Electrostatics*
- *Solid Mechanics*

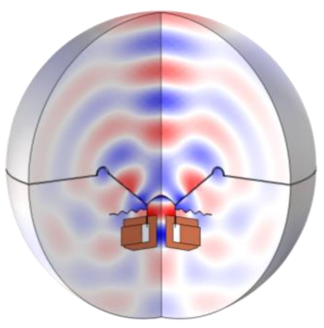


Electrostatic Drivers

Electromechanical forces

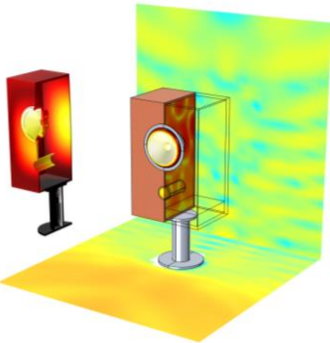
- *Electrostatics*
- *Solid Mechanics*

Numerical Methods and Space Dimensions



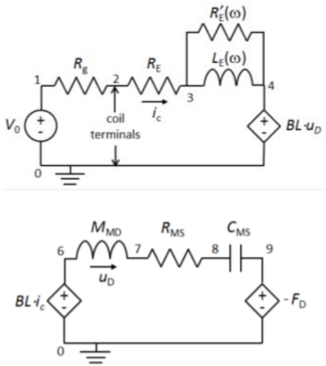
Finite Element Method (FEM)

Space dimensions: 3D (sector symmetry when possible), 2D axisymmetric, and 2D



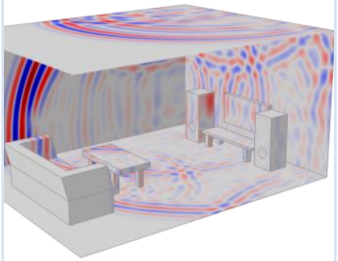
Hybrid FEM–BEM

Space dimensions: 3D



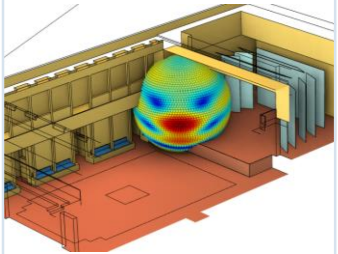
Lumped Parameter

Space dimensions: models described by algebraic equations or ODEs with no space dependency, i.e., 0D



Discontinuous Galerkin (dG)

Space dimensions: Full 3D



Ray Acoustics and Acoustic Diffusion

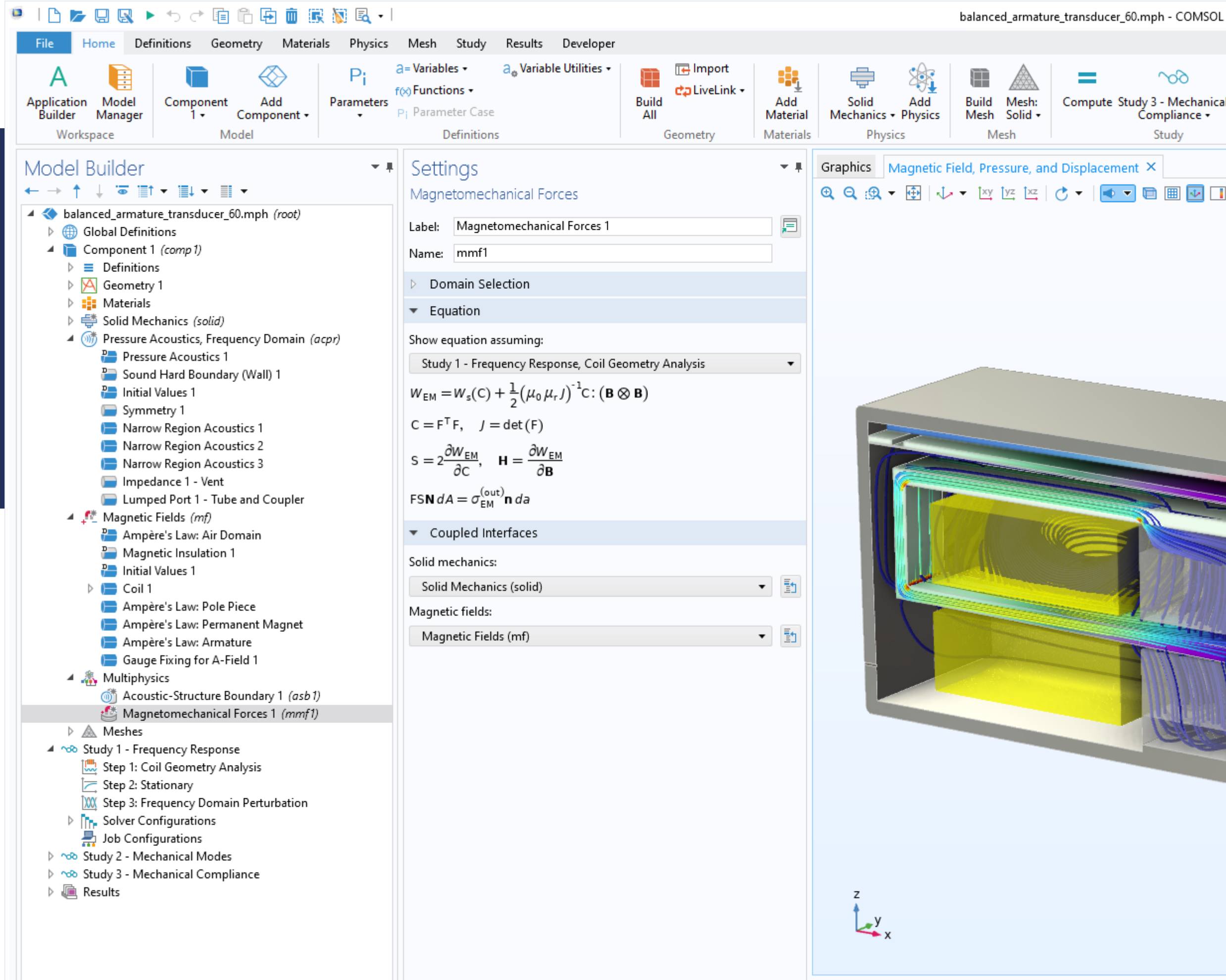
Space dimensions: 3D

Speaker driver design → Room acoustics

EXAMPLES

Full Vibro-electroacoustic Analysis

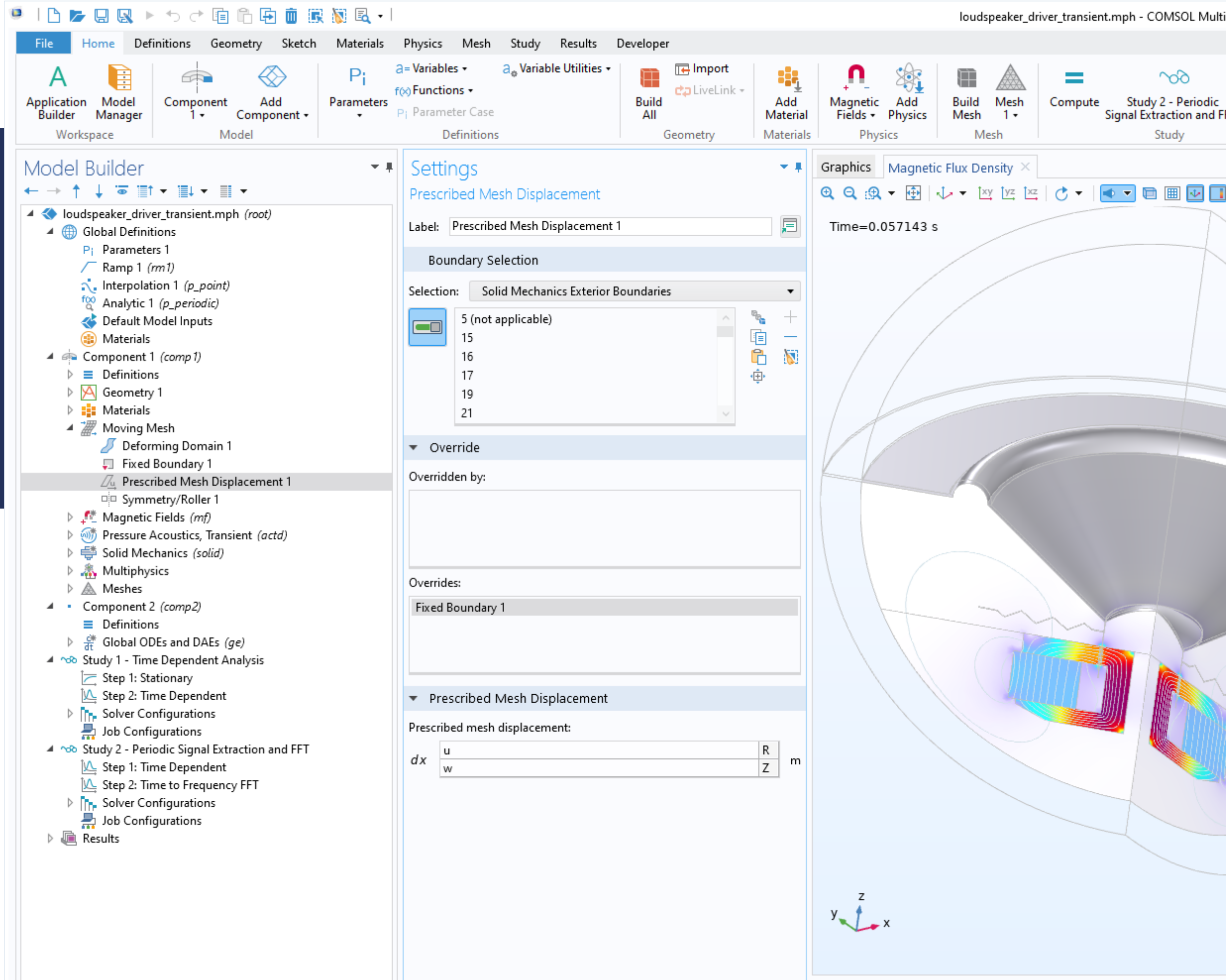
A full vibroelectroacoustic simulation of a balanced armature transducer — a high-performance miniature loudspeaker — uses the built-in *Magnetomechanical Forces* multiphysics coupling.



EXAMPLES

Full Transient, Nonlinear Analysis

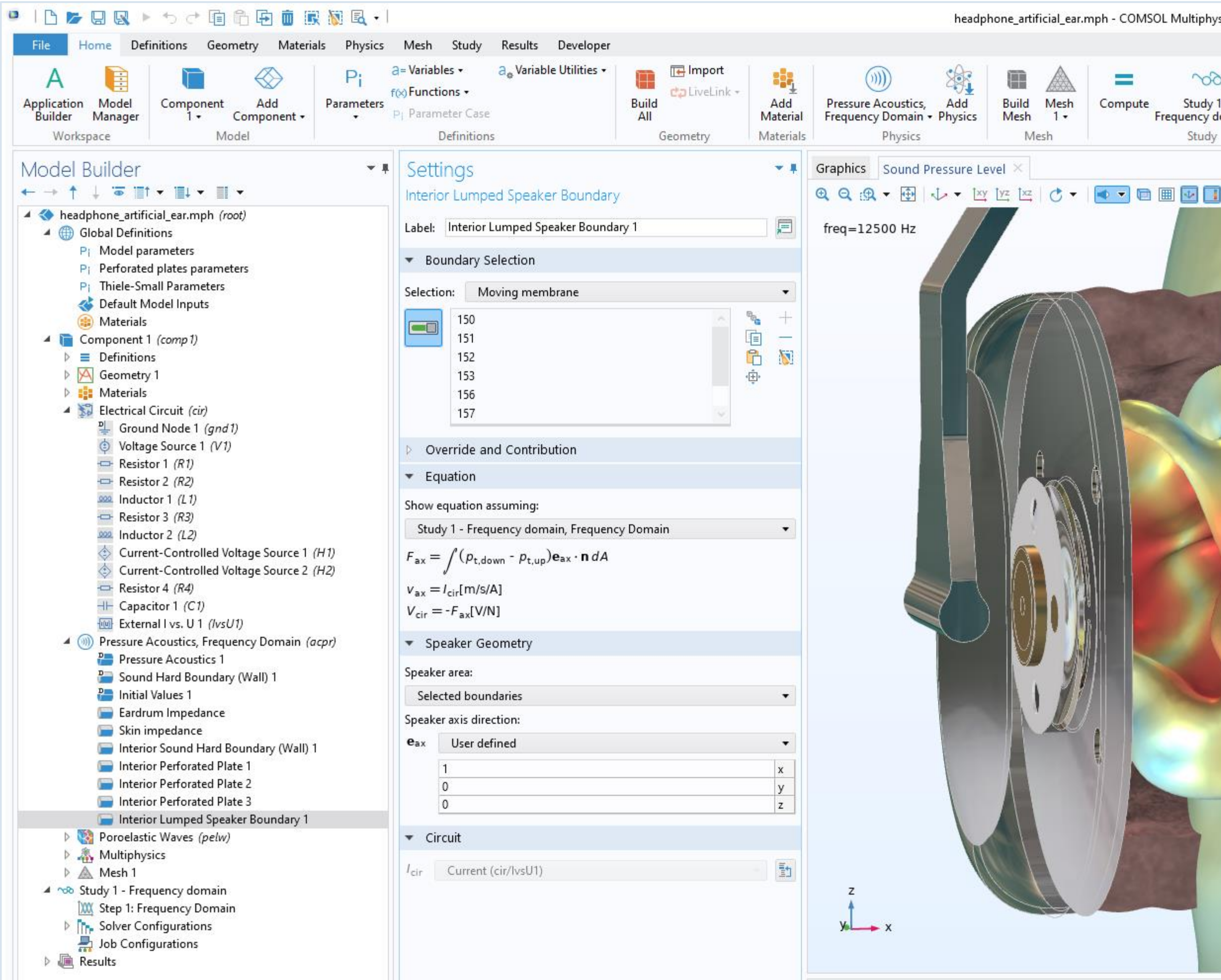
A full transient analysis allows for the modeling of the total harmonic distortion, the intermodulation distortion, and the dynamic BL curve. A moving mesh is used to capture the geometry changes with time.



EXAMPLES

Lumped Parameter Modeling

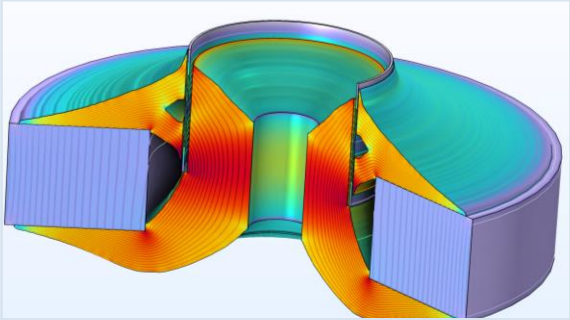
The speaker driver in the headphone is modeled through a lumped circuit and is coupled to a 3D pressure acoustics model using the *Interior Lumped Speaker Boundary* condition.



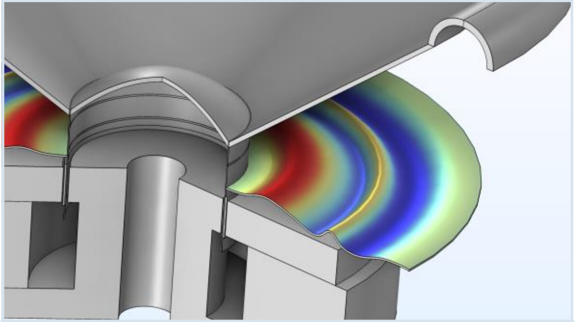
EXAMPLES

Optimization Analysis

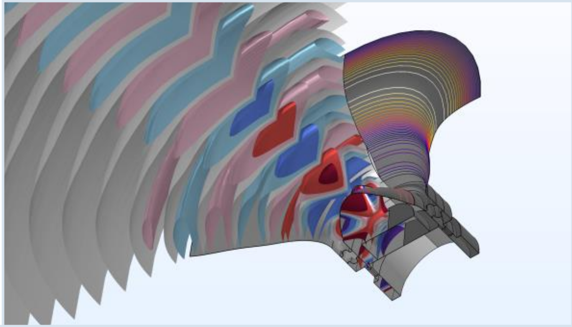
These tutorial models demonstrate how optimization methods can be used to design loudspeaker drivers and waveguides for the desired performance.



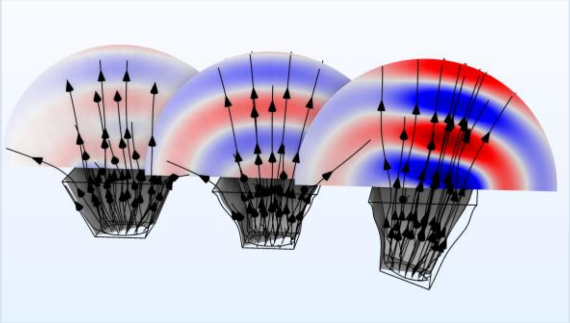
Optimization of a magnetic circuit.



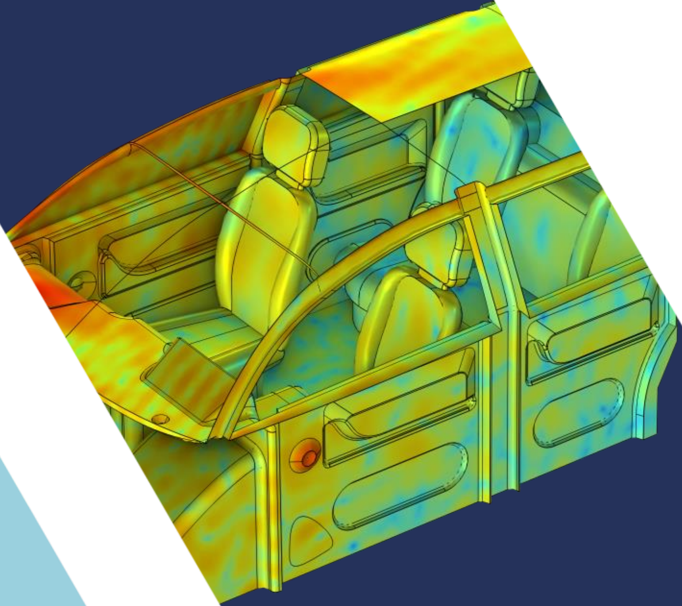
Loudspeaker spider optimization.



Tweeter dome and waveguide shape optimization.

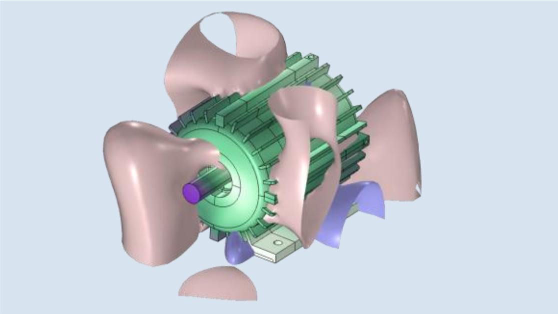


Shape optimization of a rectangular loudspeaker horn in 3D.



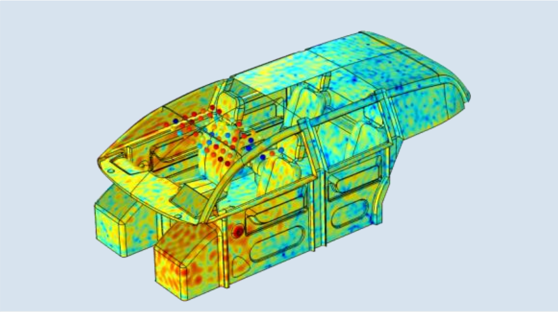
Automotive Acoustics & NVH

Automotive Acoustics Applications



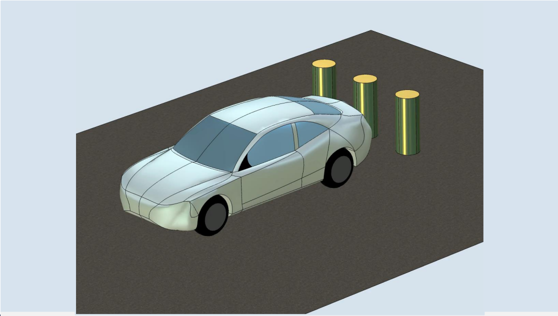
Noise and Vibrations

- Squeak and rattle noise
- Aeroacoustic noise
- Electric engine noise
- Tire noise



Car Cabin Acoustics

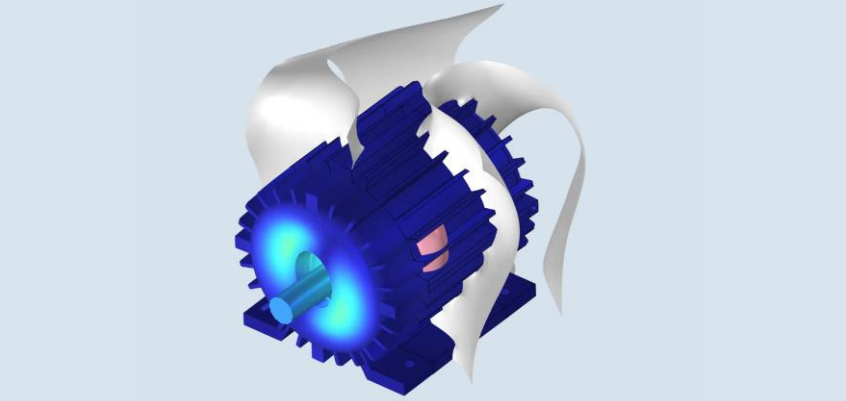
- Car cabin stereo
- Acoustic environment and personal sound zones



Sensors

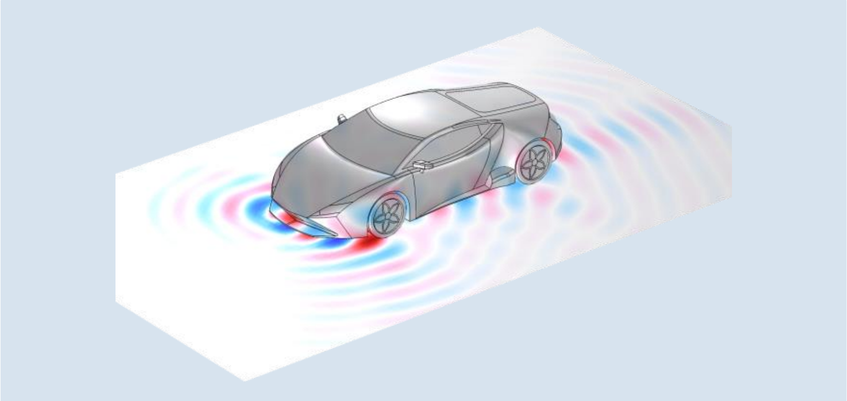
- Ultrasonic parking sensors
- Surface acoustic wave (SAW) tire pressure sensors

Solutions for Automotive Acoustics



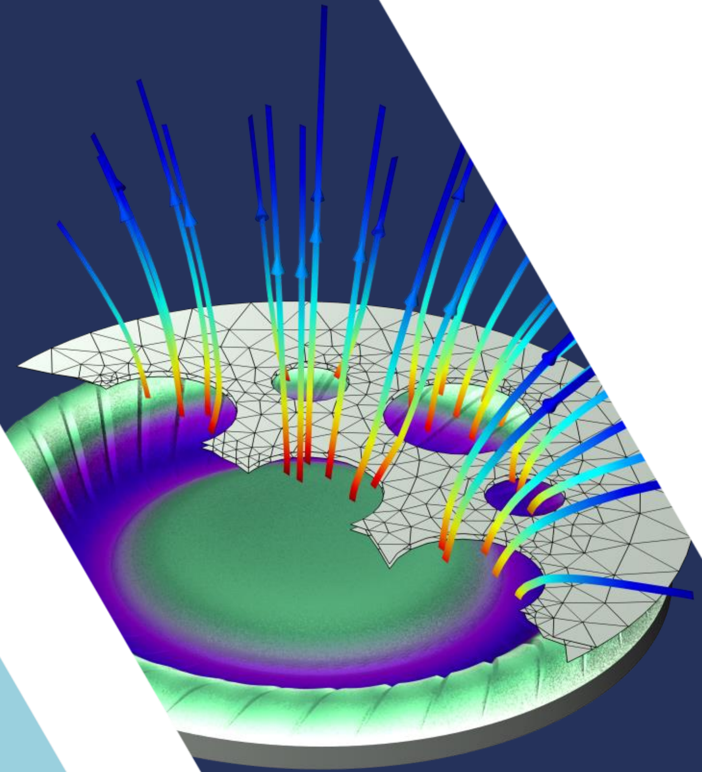
Multiphysics

- Acoustic–structure interaction
- Porous materials
- Electroacoustics
- Piezoelectricity

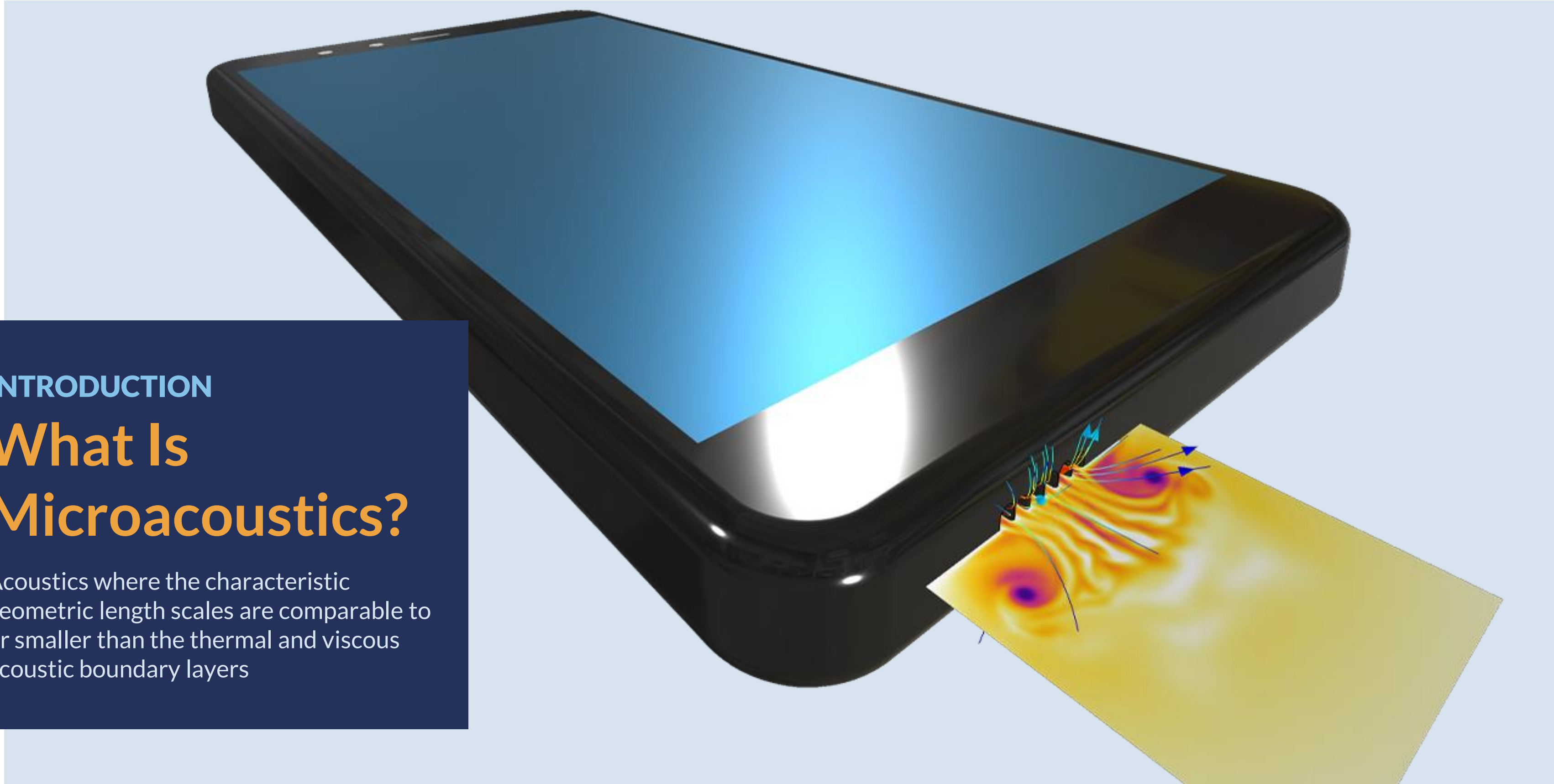


Multimethod

- Finite element method (FEM)
- Boundary element method (BEM)
- Ray tracing
- Time-explicit discontinuous Galerkin method (dG-FEM)



Microacoustics



INTRODUCTION

What Is Microacoustics?

Acoustics where the characteristic geometric length scales are comparable to or smaller than the thermal and viscous acoustic boundary layers

Thermoviscous Acoustic Features

$$i\omega\rho_t + \nabla\cdot(\rho_0\mathbf{u}_t) = 0$$

$$i\omega\rho_0\mathbf{u}_t = \nabla\cdot\boldsymbol{\sigma}$$

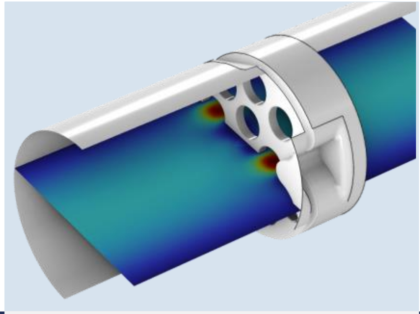
$$\rho_0 C_p(i\omega T_t + \mathbf{u}_t\cdot\nabla T_0) - \alpha_p T_0(i\omega p_t + \mathbf{u}_t\cdot\nabla p_0$$

$$\boldsymbol{\sigma} = -p_t\mathbf{I} + \mu\left(\nabla\mathbf{u}_t + (\nabla\mathbf{u}_t)^T\right) - \left(\tfrac{2}{3}\mu - \mu_B\right)(\nabla\cdot\mathbf{u}$$

$$\rho_t = \rho_0(\beta_T p_t - \alpha_p T_t)$$

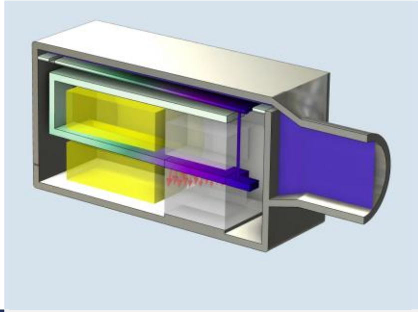
Thermoviscous Effects

Full linearized Navier–Stokes formulation, thermoviscous boundary layer impedance (BLI), and narrow region acoustics



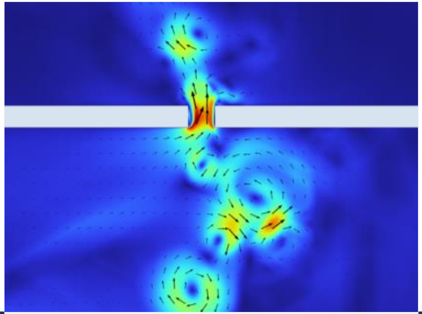
Ports

Port conditions to excite waveguides consistently and to analyze a subsystem in term of its transfer impedance



Multiphysics

Coupling to structures and pressure acoustics for transducer modeling

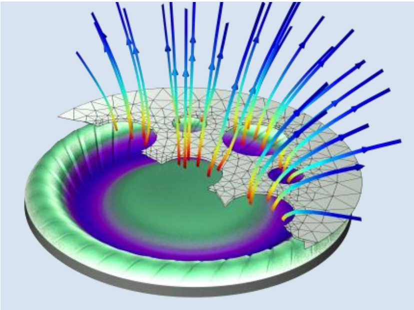


Nonlinear

Nonlinear effects included in the time domain to model distortion and added resistive losses

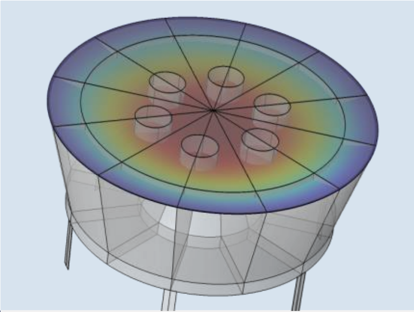
COMSOL

Thermoviscous Acoustic Applications



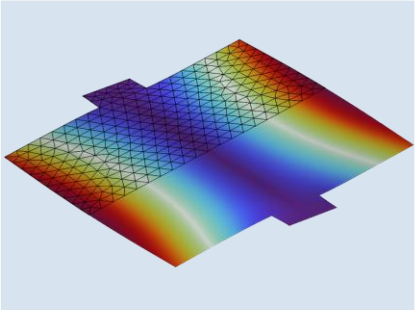
Microspeakers

Microspeakers and their operation, as well as integration into smart devices, hearing aids, and more



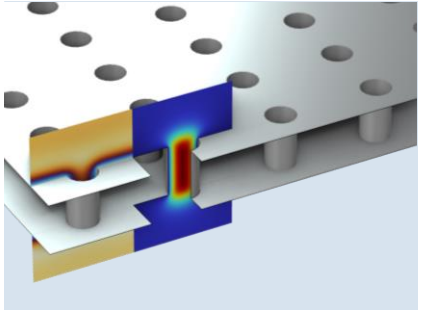
Microphones

Microphones and their operation, as well as integration into devices



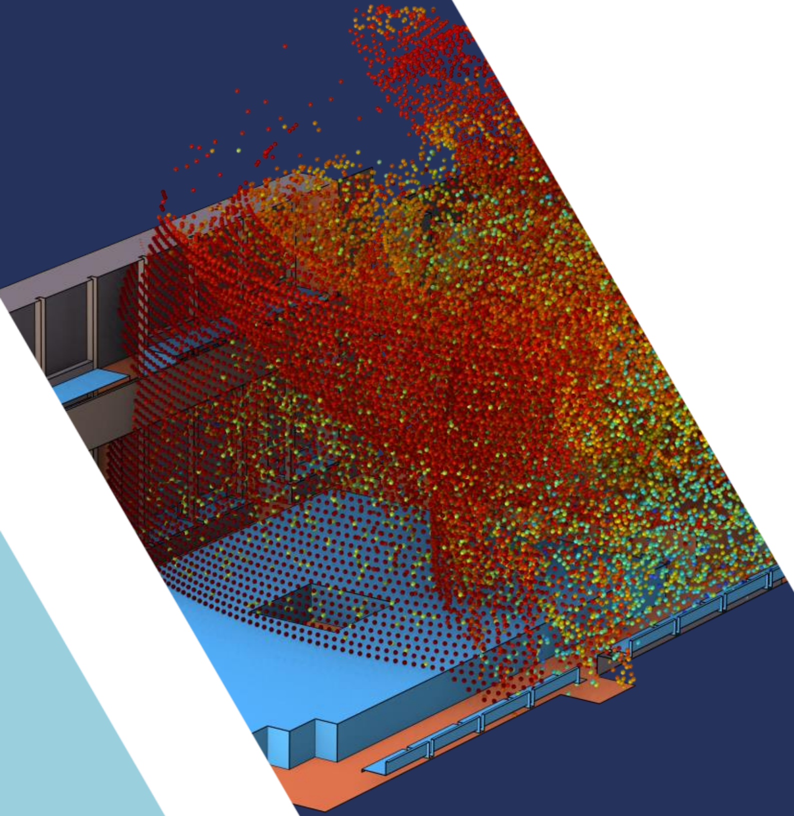
MEMS

Operation of MEMS systems such as microphones and resonators



Perforates

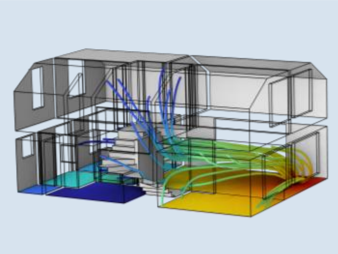
Acoustic properties of perforates and microperforated plates (MPP); transfer impedance, impedance, and absorption



Room Acoustics for Large & Small Volumes

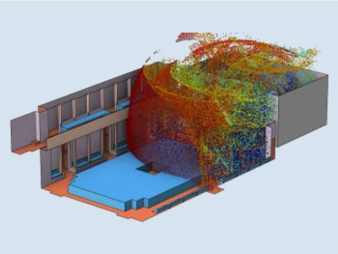
COMSOL

Acoustics Module Functionality



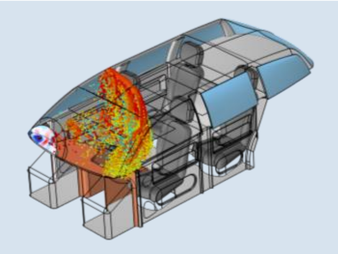
Diffusion Equation

- Steady-state energy distribution
- Transient room energy decay



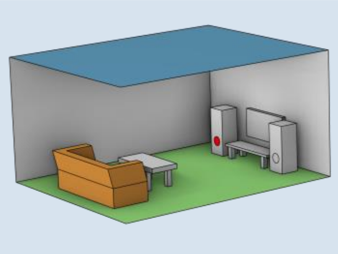
Ray Acoustics

- Room impulse response
- Room acoustics metrics



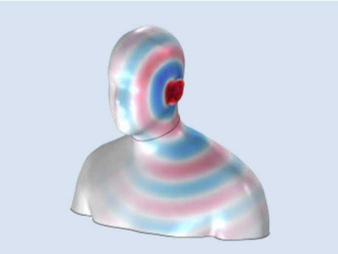
Pressure Acoustics, Frequency Domain

- Submodels and coupling
- Modal analysis
- Room impulse response



Pressure Acoustics, Time Explicit

Room impulse response



Pressure Acoustics, Boundary Elements

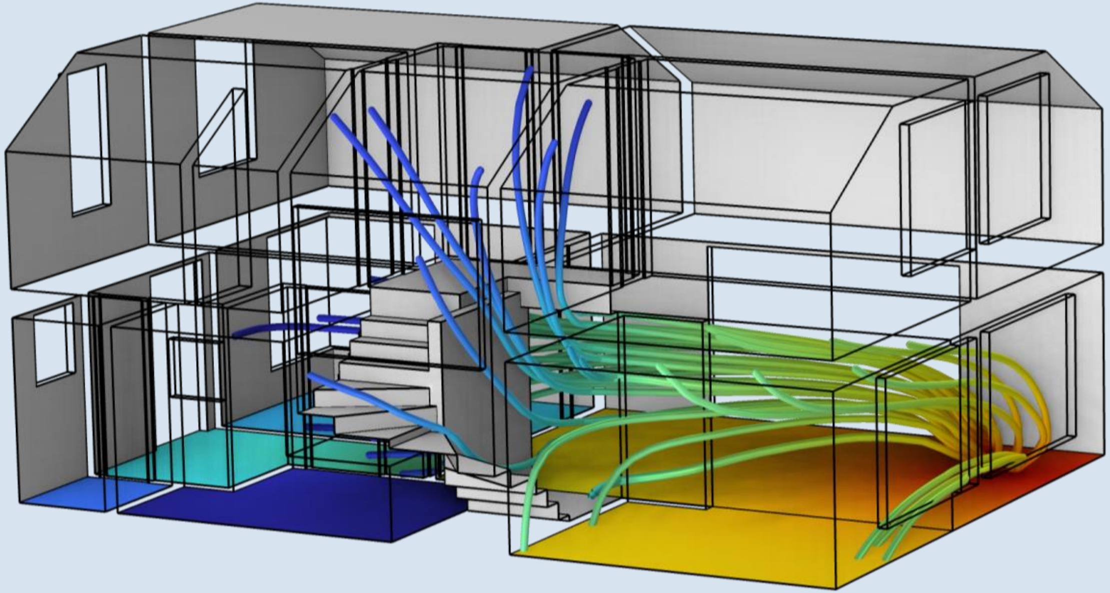
Scattering problems

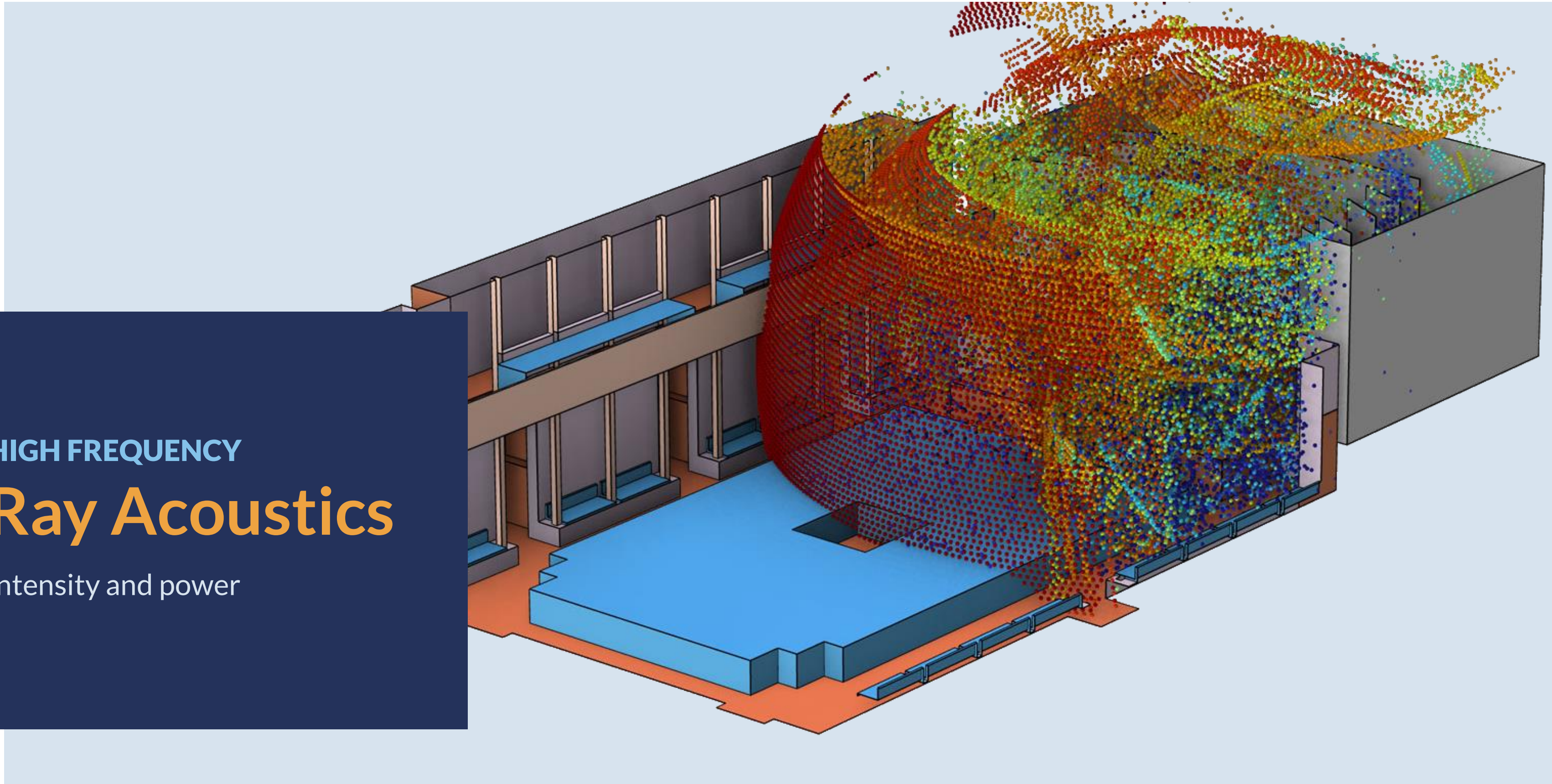
COMSOL

ACOUSTIC ENERGY

Diffusion Equation

For broadband or octave band

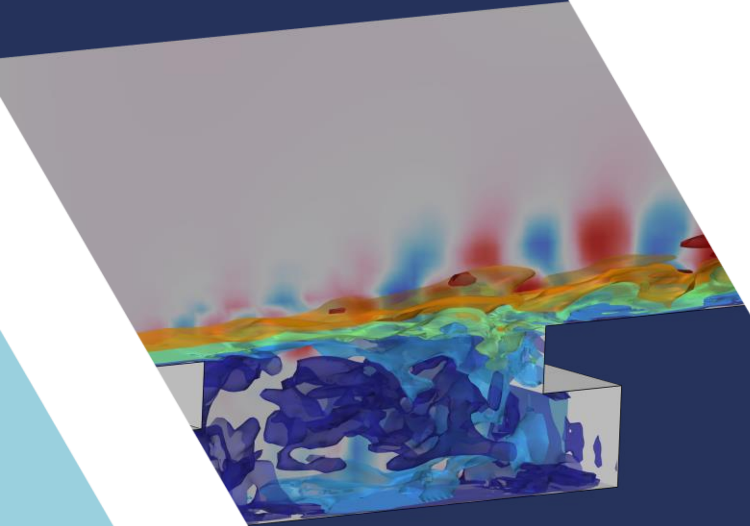




HIGH FREQUENCY

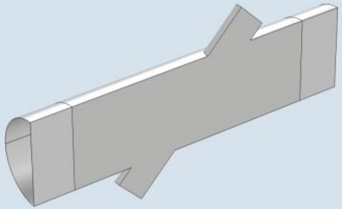
Ray Acoustics

Intensity and power



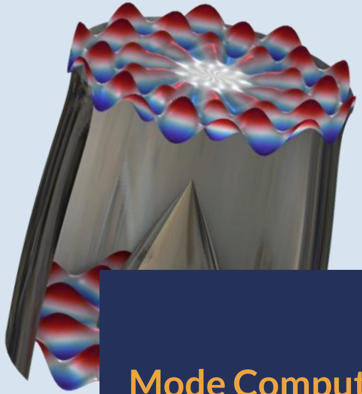
Aeroacoustics & Flow-Induced Noise

Aeroacoustic Capabilities



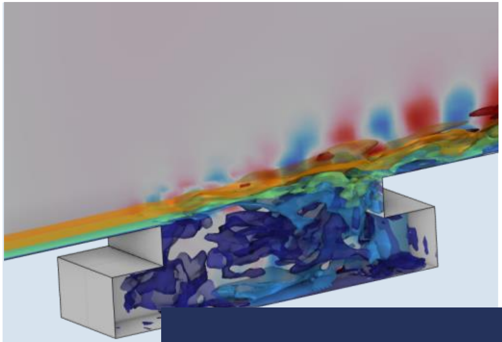
Convected Acoustics

- Acoustic propagation in the presence of a stationary background flow
- Convection, diffraction, and refraction by the flow



Mode Computation

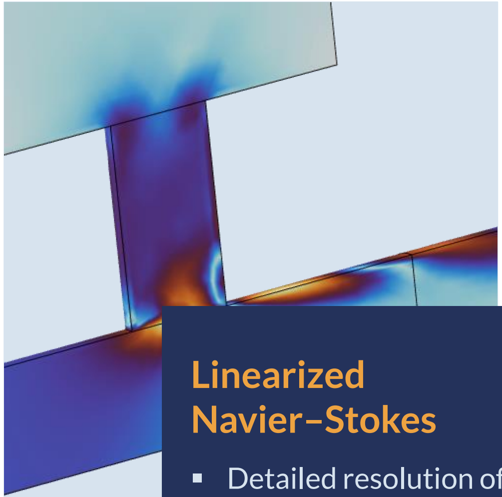
- Boundary mode interface to identify propagating and nonpropagating modes in ducts
- Essential for source characterization



Flow-Induced Noise

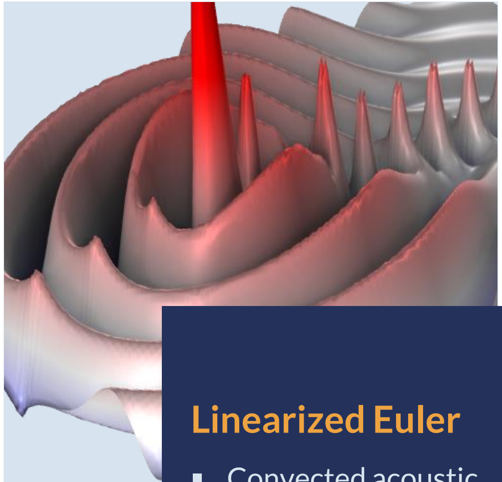
- Lighthill's acoustic analogy
- Acoustic wave equation (AWE)

Convected Acoustics



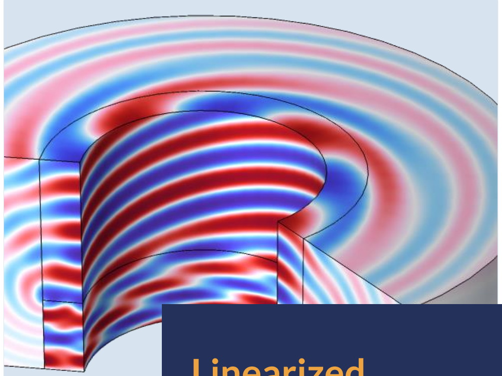
Linearized Navier–Stokes

- Detailed resolution of boundary layer effects and energy transport
- Propagation in all compressible fluids



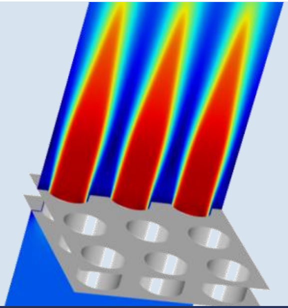
Linearized Euler

- Convected acoustic propagation in ideal gases with the linearized Euler equations



Linearized Potential Flow

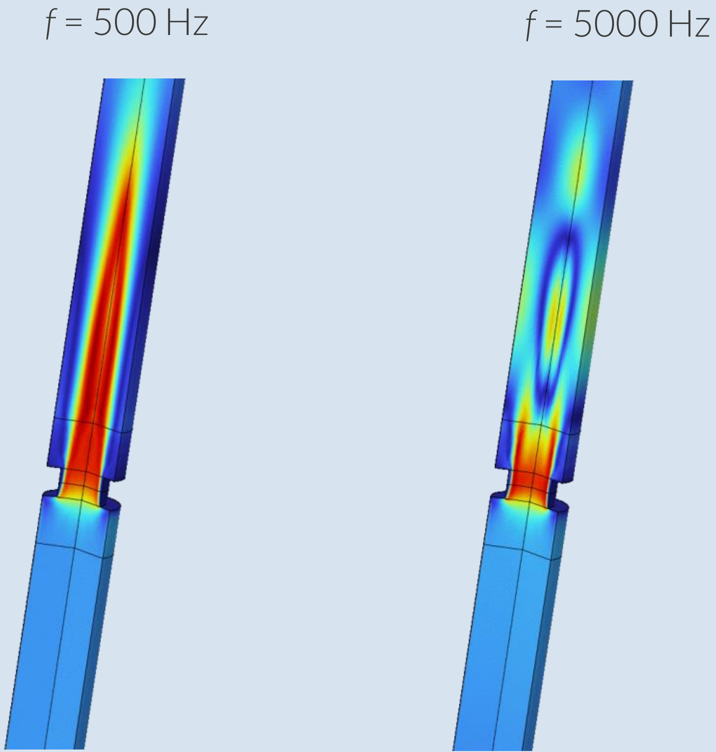
- Convected acoustic propagation in ideal irrotational potential flows
- Ideal for fast analysis



SUBMODELING

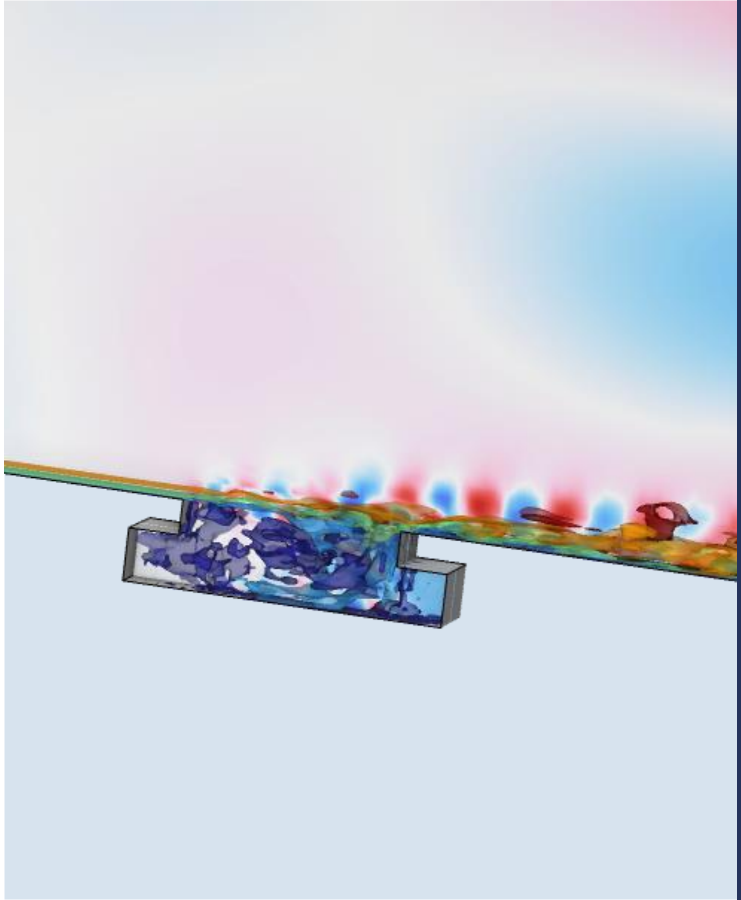
Transfer Impedance of Perforate with Bias Flow

Complex interaction of acoustic field and flow gradients through reactive terms in the linearized Navier–Stokes equations



Flow-Induced Noise

- Lighthill's acoustic analogy
- Acoustic wave equation (AWE)
- Acoustic sources extracted from large eddy simulation (LES): CFD Module
- Dedicated transient mapping study

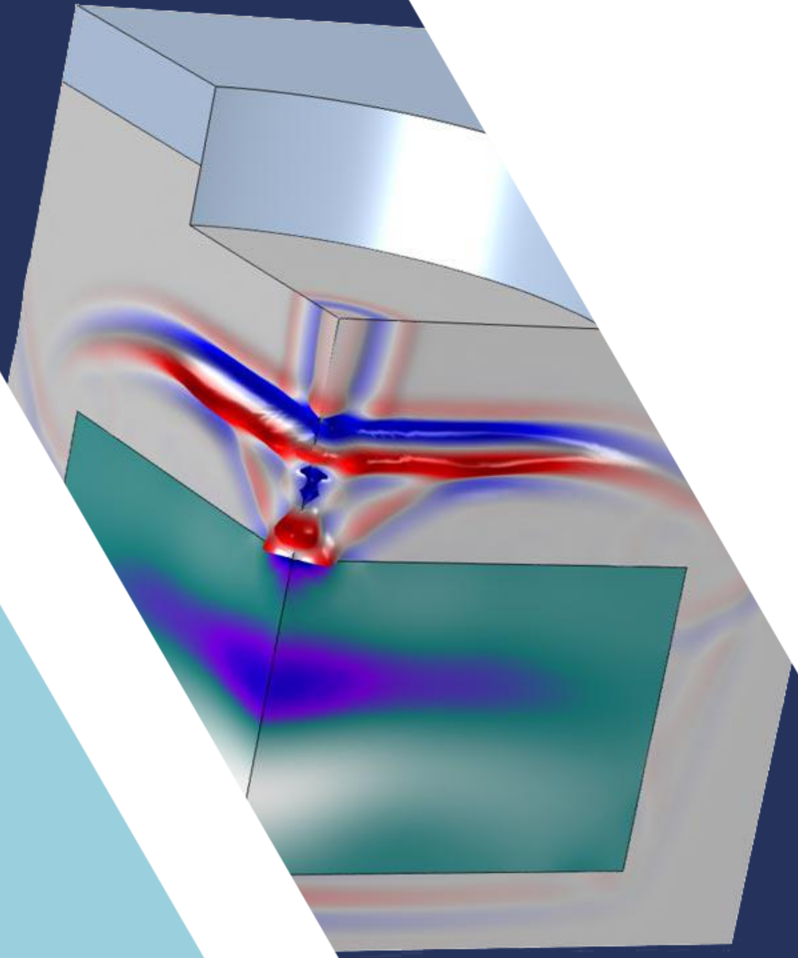


Resolve Time and Space

The LES model needs to resolve the flow in both space and time.

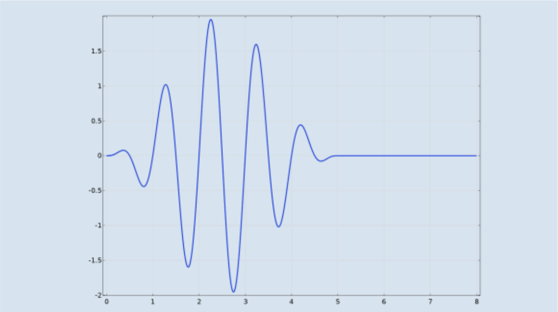
Computational Effort

LES simulations require good computational resources.



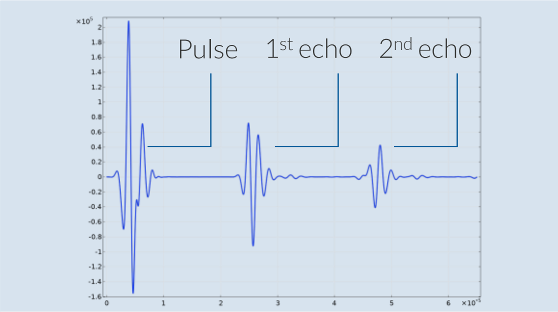
Ultrasound & Nondestructive Testing

Modeling Ultrasonic Wave Propagation in the Time Domain



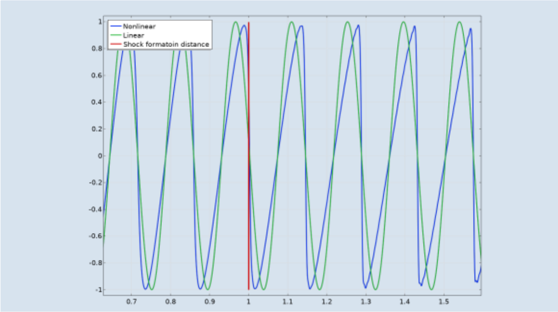
Signal Type

- Pulses
- Modulated sinusoidal signals



Operating Principle

- Sonic reflection (pulse-echo) measurement
- Time of flight computation



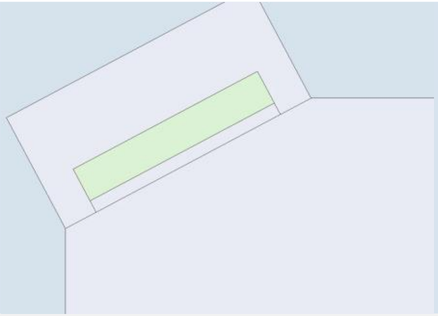
Nonlinear Effects

- High harmonic generation
- Shock waves

Physics Interfaces for Modeling Ultrasound

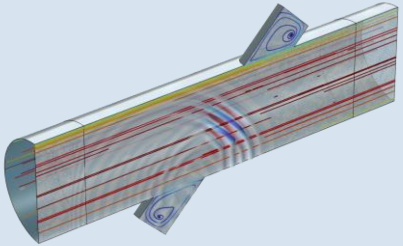
Linear Elastic Solids

Elastic Waves, Time Explicit



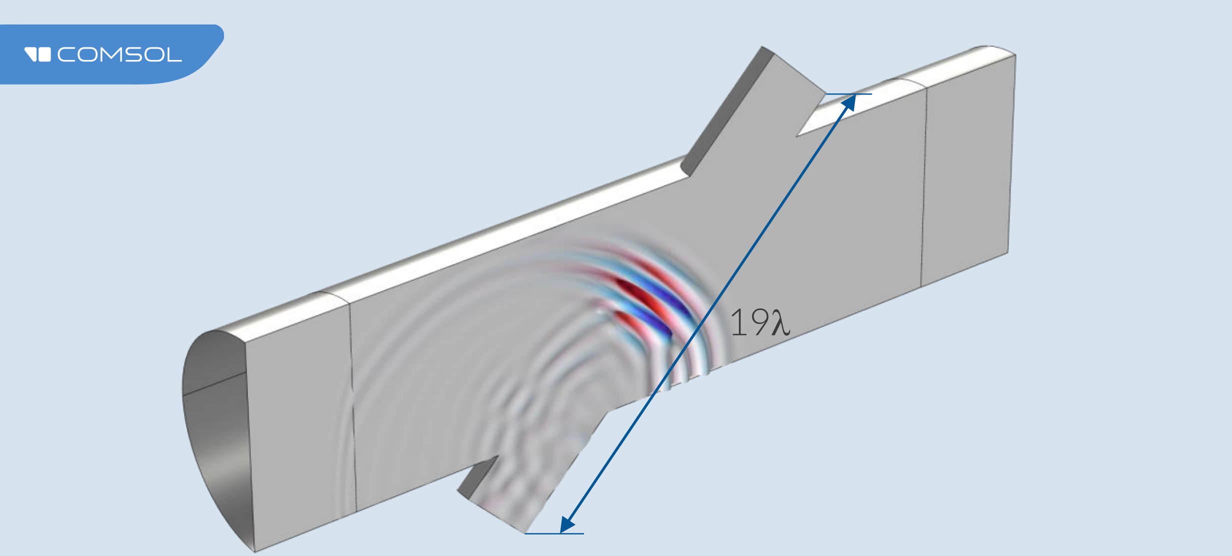
Piezoelectric Solids

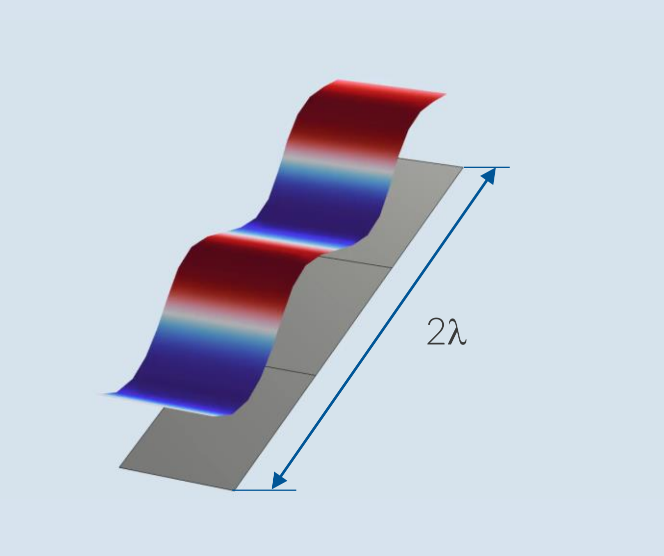
Piezoelectric Waves, Time Explicit



Quiescent and Moving Fluids

- *Pressure Acoustics, Time Explicit*
- *Nonlinear Pressure Acoustics, Time Explicit*
- *Convected Wave Equation, Time Explicit*

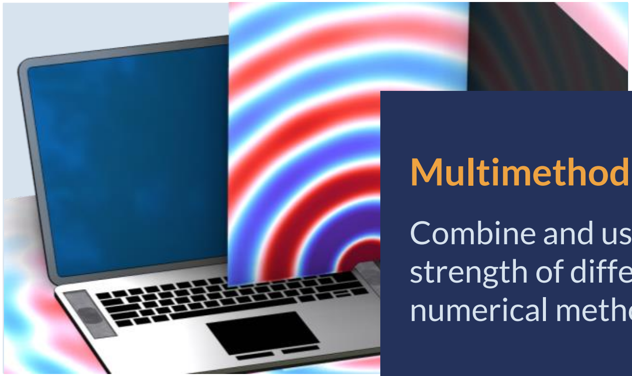




Time-Explicit Discontinuous Galerkin FEM (dG-FEM)

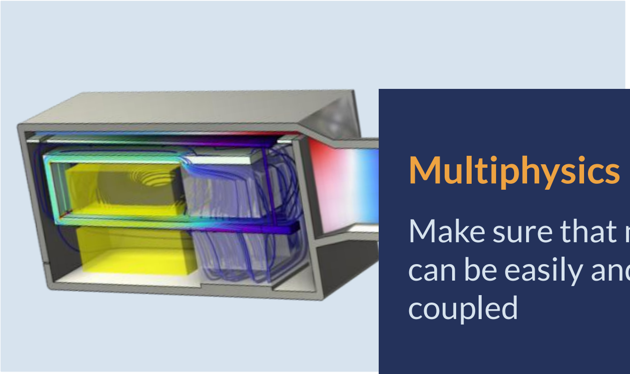
- Suited to acoustically large problems ($L \gg \lambda$)
- Uses higher-order discretization (4th order by default)
- Memory lean and high-performance computing (HPC) enabled

The COMSOL® Software Is the Right Tool for the Job



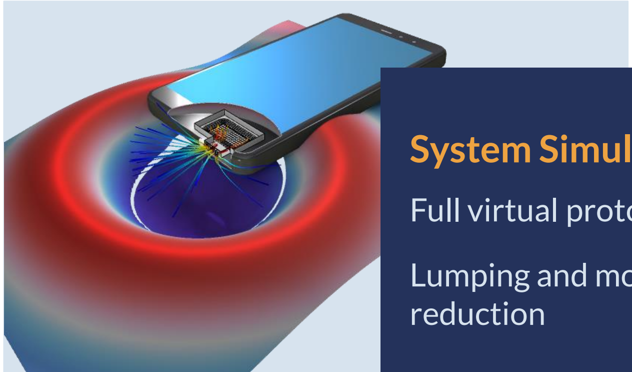
Multimethod

Combine and use the strength of different numerical methods



Multiphysics

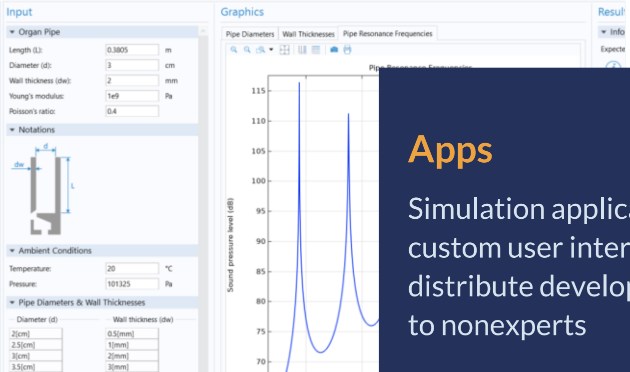
Make sure that most physics can be easily and flexibly coupled



System Simulation

Full virtual prototypes

Lumping and model reduction



Apps

Simulation applications with custom user interfaces help distribute development tasks to nonexperts