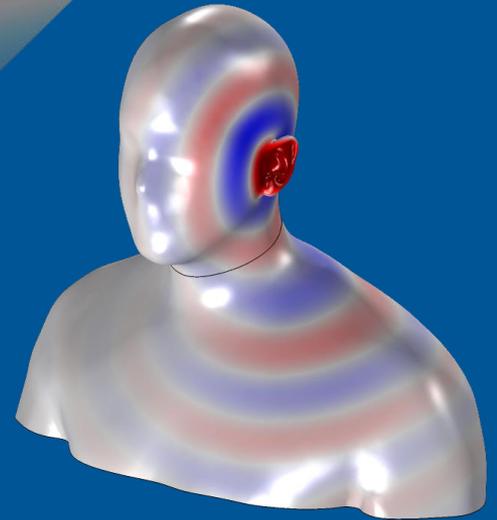
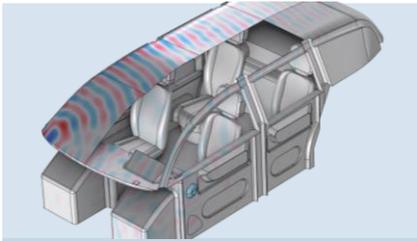


# Acoustics Module

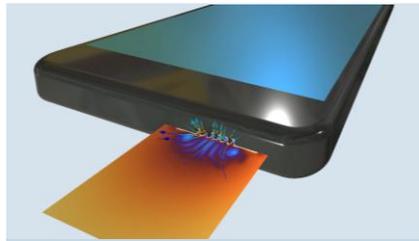


# The Acoustics Module



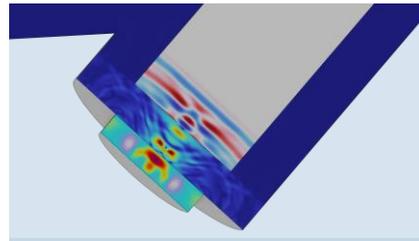
## Pressure Acoustics

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



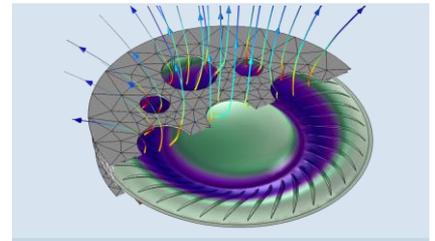
## Thermoviscous Acoustics

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



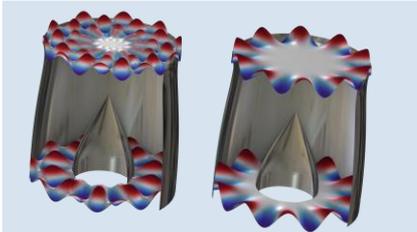
## Elastic Waves

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



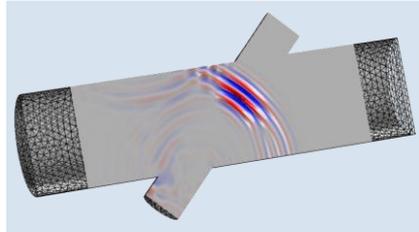
## Acoustic-Structure Interaction

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



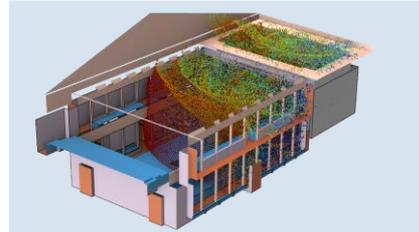
## Aeroacoustics

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



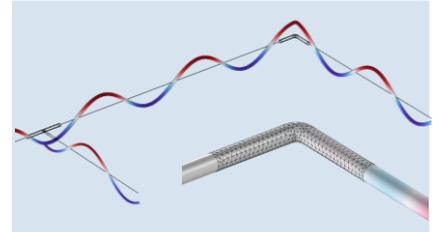
## Ultrasound

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

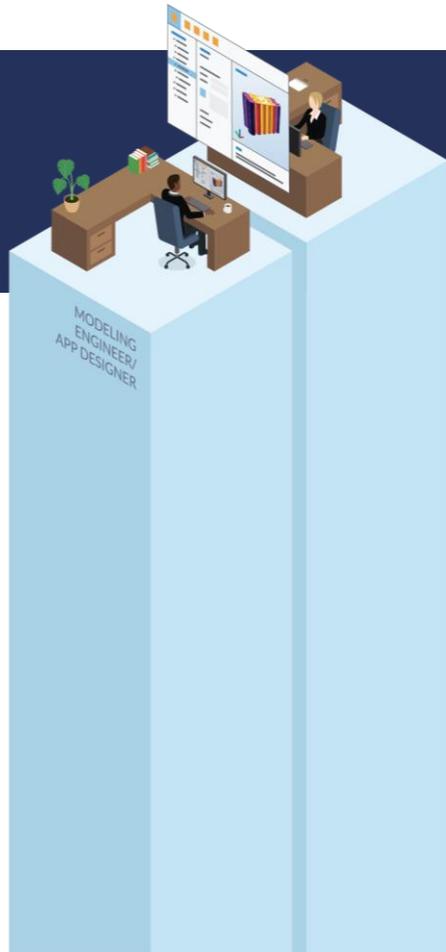
Wave propagation in 1D pipe structures with background flow effects; 1D to 3D coupling for system simulation



# COMSOL 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

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

Geometry

Materials

Physics

Mesh

Studies

Results

The screenshot displays the COMSOL Multiphysics software interface. The top menu bar includes File, Home, Definitions, Geometry, Materials, Physics, Mesh, Study, Results, and Developer. The left sidebar contains the Model Builder, Application Builder, and Model Manager. The main workspace is divided into three panels: Model Builder, Settings, and Graphics.

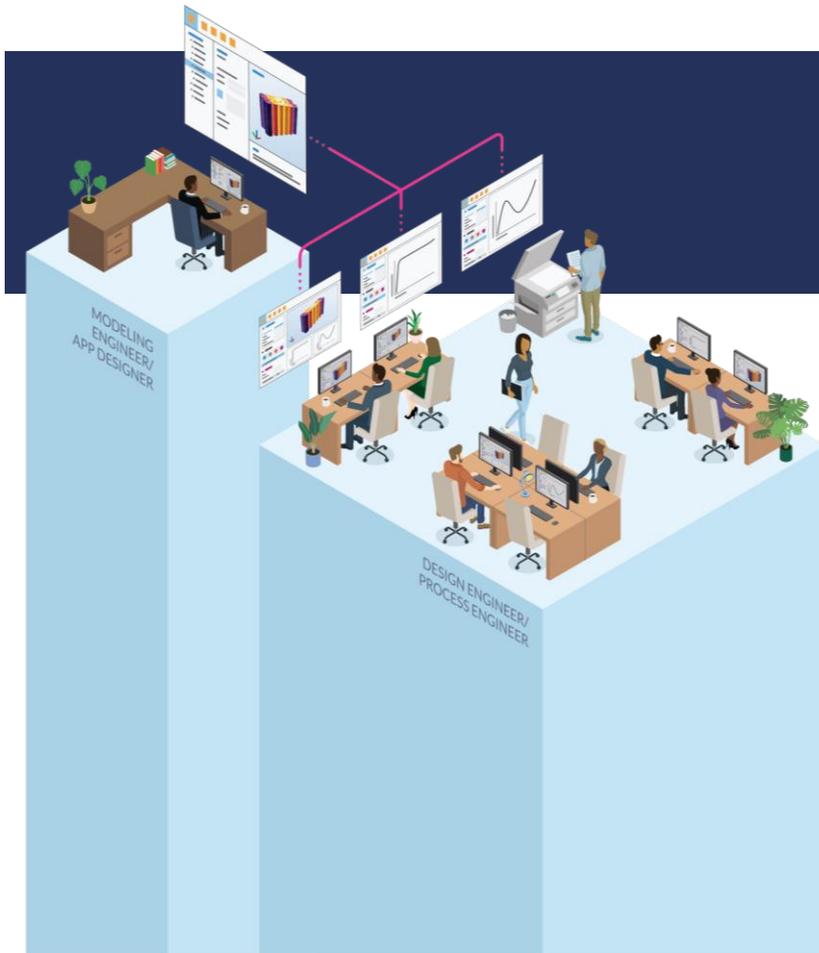
**Model Builder:** Shows a tree view of the model structure. The root is 'battery\_app.mph (root)', which contains Global Definitions, Component 1 (comp1), Component 2 (comp2), Definitions, Geometry 1, Materials, Physics, Mesh, and Studies. The 'Materials' section is expanded, showing Air (mat1), Aluminum (mat2), Copper (mat3), Active Battery Material (mat4), Heat Transfer in Solids (ht), and Lumped Battery 2 (lb2). The 'Physics' section is expanded, showing Cell Equilibrium Potential 1, Voltage Losses 1, and Multiphysics. The 'Multiphysics' section is expanded, showing Electrochemical Heating 1 (ech1). The 'Studies' section is expanded, showing Study 1 and Study 2, each with Step 1: Time Dependent and Solver Configurations. The 'Results' section is expanded, showing Datasets, Derived Values, and Tables. The 'Tables' section is expanded, showing Load Cycle Data, Open Circuit Voltage, Cell Voltage, and Volume. The 'Probe Plot Group 1' section is expanded, showing Experimental Data, Open Circuit Voltage, Cell State-of-Charge, Cell Voltage, Voltage Losses and Load, Max/Average Battery Temperature, Temperature - Slice, Temperature - Volume, Battery Pack, Export, and Reports.

**Settings:** Shows the configuration for 'Electrochemical Heating 1'. The label is 'Electrochemical Heating 1' and the name is 'ech1'. The domain selection is set to 'All domains'. The boundary selection is set to '251 (not applicable)'. The equation is set to 'Study 1, Time Dependent'. The equation is  $\rho C_p \mathbf{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q_h$ . The heat source term is  $Q_h = \left( \eta_{IR} + \eta_{act} + T \frac{\partial E_{OCV}(SOC)|_{x=1,T}}{\partial T} \right)_{cell} + Q_{mix}$ . The mixing term is  $Q_{mix} = \frac{3Q_{cell,0}}{\tau} \int_0^1 \frac{\partial E_{OCV,therm}}{\partial SOC} \frac{\partial SOC}{\partial x} \frac{\partial SOC}{\partial x} x^2 dx$  for a pa. The coupled interfaces are 'Lumped Battery 2 (lb2)' and 'Heat Transfer in Solids (ht)'. The electrochemical interface is 'Lumped Battery 2 (lb2)' and the heat transfer interface is 'Heat Transfer in Solids (ht)'. The equation is shown assuming 'Study 1, Time Dependent'.

**Graphics:** Shows a 3D visualization of a battery pack. The time is 0.2 h. The surface temperature is shown. The battery pack consists of multiple cylindrical cells arranged in a grid. The cells are colored in a gradient from yellow to purple, representing different temperatures. The top surface of the battery pack is highlighted in purple.

**Messages:** Shows a table with columns for SOC and Open circuit voltage(V). The table contains the following data:

SOC	Open circuit voltage(V)
0.0000	1.3104



# Application Builder

**Supports extending modeling to specific engineering and technical applications**

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

# Application Builder

Go between:  
Model Builder  
Application Builder  
Model Manager

The screenshot displays the COMSOL Multiphysics Application Builder interface. The top menu bar includes File, Home, Definitions, Geometry, Materials, Physics, Mesh, Study, Results, and Developer. The main workspace is divided into three panels:

- Model Builder:** Shows a tree view of the model structure for 'battery\_app.mph'. The selected item is 'Electrochemical Heating 1 (ech1)'. The tree includes Global Definitions, Component 1 (comp1), Component 2 (comp2), Definitions, Geometry 1, Materials (Air, Aluminum, Copper, Active Battery Material), Heat Transfer in Solids (ht), Lumped Battery 2 (lb2), Cell Equilibrium Potential 1, Voltage Losses 1, Multiphysics, and Mesh 1.
- Settings:** Shows the configuration for 'Electrochemical Heating 1'. The domain selection is set to 'All domains'. The equation is set to 'Study 1, Time Dependent'. The governing equation is:
 
$$\rho C_p \mathbf{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q_h$$

$$Q_h = \left( \eta_{ir} + \eta_{act} + T \frac{\partial E_{ocv}(SOC|_{x=1}, T)}{\partial T} \right) I_{cell} + Q_{mix}$$

$$Q_{mix} = \frac{3Q_{cell,0}}{\tau} \int_0^1 \frac{\partial E_{ocv,therm}}{\partial SOC} \frac{\partial SOC}{\partial x} \frac{\partial SOC}{\partial x} x^2 dx \quad \text{for a pa}$$

$$E_{ocv,therm} = E_{ocv,ref}(SOC) - T_{ref} \frac{\partial E_{ocv}(SOC)}{\partial T}$$
- Graphics:** Shows a 3D visualization of the battery cell structure. The time is set to 0.2 h, and the surface is labeled 'Temperature (K)'. The visualization shows a stack of cylindrical cells with a yellow mesh on top.

# Application Builder

Forms and UI widgets

Access model parameters and settings

Methods to create code snippets in Java®

The screenshot displays the COMSOL Application Builder interface for a project named "submarine\_cable\_analyzer.mph". The interface is divided into several key areas:

- Top Toolbar:** Contains standard application menus (File, Home, Form) and various tool icons for form design, including Input Field, Text Label, Button, Data Display, Check Box, Graphics, and more. It also includes a "Form" section with Grid, Sketch, and Layout tools, and a "Test" section with Test Application, Apply Changes, Preview Form, and Test in Web Browser buttons.
- Application Builder (Left Panel):** Shows a hierarchical tree view of the project structure. The "Main" form is selected, and its sub-elements (main, navigation, graphics, Input, Output, Events, Methods, Libraries) are visible. The "Methods" folder contains a list of Java snippets for interacting with the model, such as "navigate", "checkAndRefresh", "flagInputChanged", "solveCableModel", and "exportToExcel".
- Form Editor (Center):** The main workspace for designing the user interface. It is currently displaying a "Cable Cross Section" form with a "Phase Properties" section. This section includes input fields for "Conductor diameter" (26.2 mm), "Insulation thickness" (24.0 mm), "Insulation outer diameter" (75.9 mm), "Screen thickness" (2.9 mm), and "Screen outer diameter" (83.4 mm). Below this is a "Phase" section with "Phase outer diameter" (89.2 mm) and an "Armor Properties" section with "Armor thickness" (5.6 mm), "Armor central diameter" (205.6 mm), and "Number of armor wires" (110). The form editor window is titled "Form Editor window for interactive UI design using drag and drop".
- Right Panel:** Shows the "Settings" for the form, including fields for Name, Title, Icon, Size, Margins, Horizontal/Vertical alignment, Dialog Size, and Grid Layout.

Annotations with blue arrows point from the text labels on the left to the corresponding parts of the interface: "Forms and UI widgets" points to the top toolbar; "Access model parameters and settings" points to the "Methods" folder in the Application Builder; and "Methods to create code snippets in Java®" points to the list of methods in the "Methods" folder.



# 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

Design

Operating conditions

Results

Graphics

Untitled.mph - Li Battery Pack Designer

File Home

Battery Cell Battery Pack Compute Parameters Open Circuit Voltage Experimental Data Cell State-of-Charge Cell Voltage Voltage Losses Update Design Mesh Compute Temperature Graph Animate Show Bus Bar Show Air Show Edges Numerical Results

Battery Pack

### Battery Pack

▼ Design

Packing type: Offset

Number of batteries in series: 20

Number of batteries in parallel: 10

Battery diameter: 21 mm

Battery height: 70 mm

Terminal diameter: 6 mm

Terminal thickness: 1 mm

Bus bar thickness: 1 mm

Serial connector width: 3 mm

Parallel connector width: 1 mm

▼ Conditions

C rate: 4

Initial state-of-charge: 1

Final state-of-charge: 0.2

Initial/external temperature: 20 °C

Heat transfer coefficient, sides: 30 W/(m<sup>2</sup>·K)

Heat transfer coefficient, top: 30 W/(m<sup>2</sup>·K)

Heat transfer coefficient, bottom: 5 W/(m<sup>2</sup>·K)

Graphics

Time=0.2 h

Surface: Temperature (K)

Numerical Results

Export to Text Export to Excel Clear Table

Variable name	Solution 1
Maximum battery temperature [degC]	44.7612
Average battery temperature [degC]	30.6030
Battery pack volume [m <sup>3</sup> ]	0.00585087
Battery capacity [A·h]	4
Optimality tolerance	0.01
Ohmic overpotential at 1C [V]	0.0045162
Diffusion time constant [s]	1374.4
Dimensionless charge exchange current	0.86471
Packing type	Offset
Batteries in series	20
Batteries in parallel	10
Battery diameter [mm]	21
Battery height [mm]	70
Terminal diameter [mm]	6
Bus bar thickness [mm]	1
Serial connector width [mm]	3
Parallel connector width [mm]	1
Battery density [kg/m <sup>3</sup> ]	2000
Battery heat capacity [J/(kg·K)]	1400
Thermal conductivity, in plane [W/(m·K)]	30
Thermal conductivity, cross plane [W/(m·K)]	1
C rate	4
Initial state of charge	1
Final state-of-charge	0.2
Initial/external temperature [degC]	20
Heat transfer coefficient, sides [W/(m <sup>2</sup> ·K)]	30
Heat transfer coefficient, top [W/(m <sup>2</sup> ·K)]	5
Heat transfer coefficient, bottom [W/(m <sup>2</sup> ·K)]	30
Mesh size	Normal



# 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

# Model Manager

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

The screenshot displays the COMSOL Model Manager interface. The top navigation bar includes 'File', 'Home', 'Database', and 'CsDevelop'. The 'Database' tab is active, showing options for 'Server Database', 'Add Database', and 'Databases'. The 'Model Manager' pane shows a search for 'coupler' in a 'Server Database (Application Library/Daily)'. The search results are displayed in a tree view under the 'Daily' branch, listing various models such as 'Acoustics\_Module', 'Electroacoustic\_Transducers', 'Tutorials\_Thermoviscous\_Acoustics', 'Liquid\_and\_Gas\_Properties\_Module', 'Molecular\_Flow\_Module', 'Particle\_Tracing\_Module', and 'RF\_Module'. The 'Pressure Reciprocity Calibration Coupler with Detailed Moist Air Material Properties' model is highlighted. The 'Settings' pane on the right shows the application location and version information.

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

# The Acoustics Module - Is It Really “Multi”?

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

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

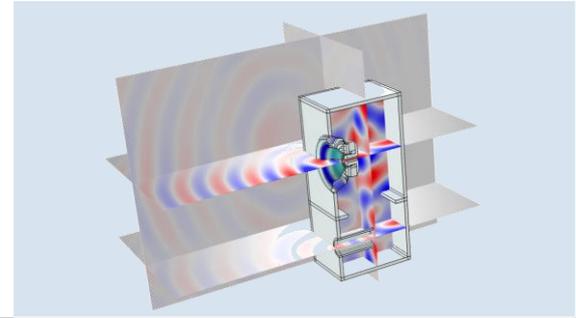
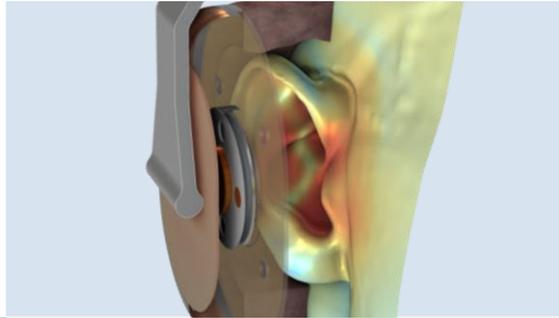
$$\rho \frac{\partial \mathbf{u}_t}{\partial t} + \nabla \cdot (\rho_t \mathbf{l}) = \mathbf{q}_d$$

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

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

$$\beta = 1 + \frac{B}{2A}$$

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



## 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

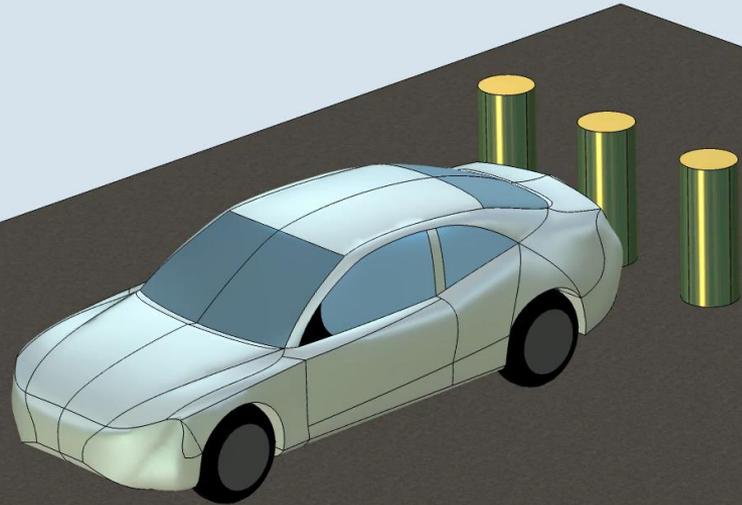
# Ultrasonic Car Parking Sensor

## Multiphysics

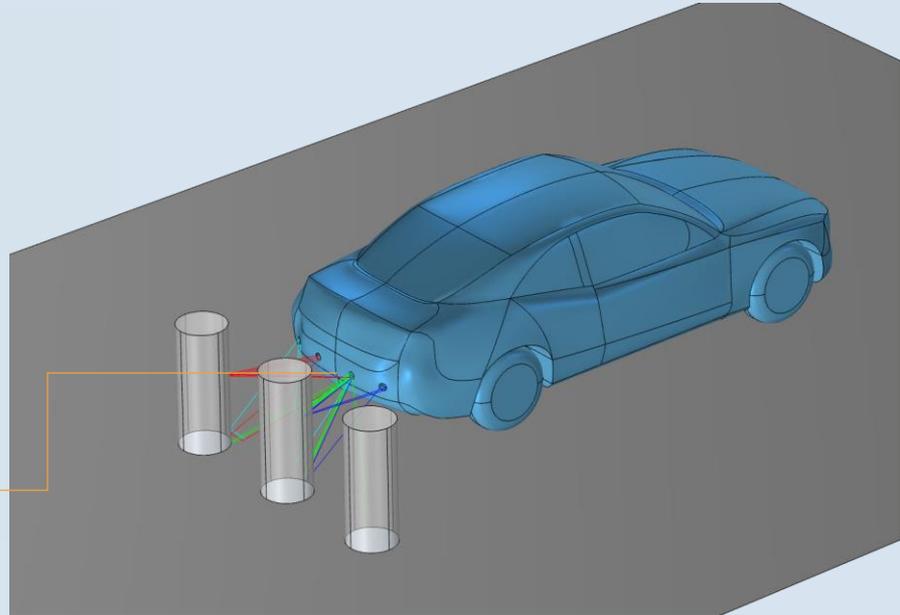
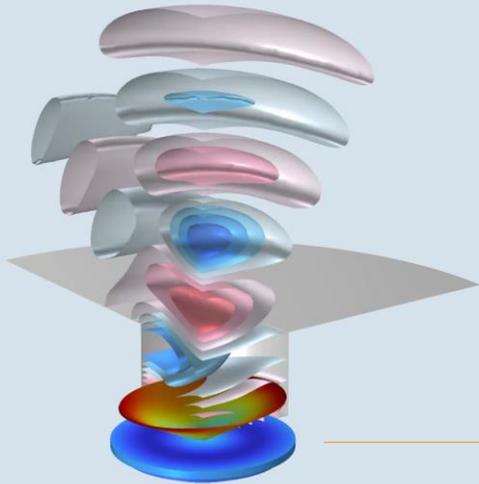
- Piezoelectricity
- Acoustic-structure interaction

## Multimethod

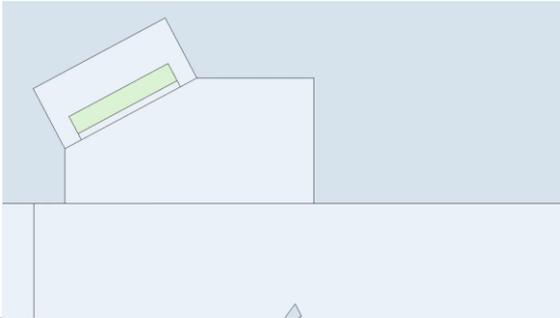
- Finite elements
- Ray tracing



# Ultrasonic Car Parking Sensor

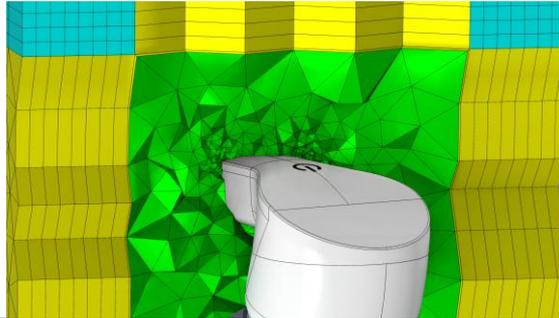


# The Latest News (COMSOL Multiphysics® Version 6.0)



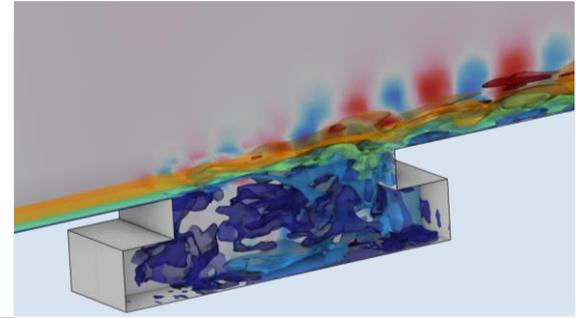
## Piezoelectric Waves, Time Explicit

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



## Physics-Controlled Mesh

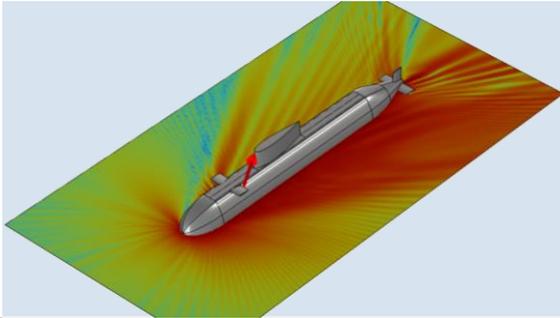
- Automated best-practices-based meshing
- Physics and material parameters analyzed



## Introducing Flow-Induced Noise

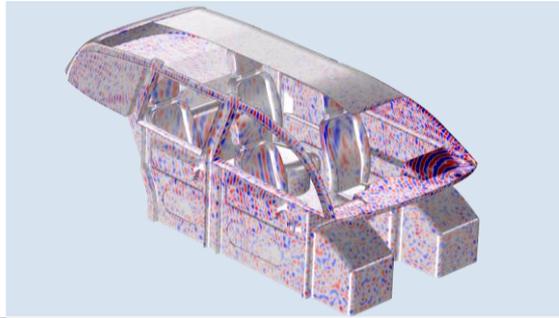
- Lighthill's acoustic analogy
- Acoustic wave equation (AWE)
- Multiphysics coupling and transient mapping

# The Latest News (COMSOL Multiphysics® Version 6.0)



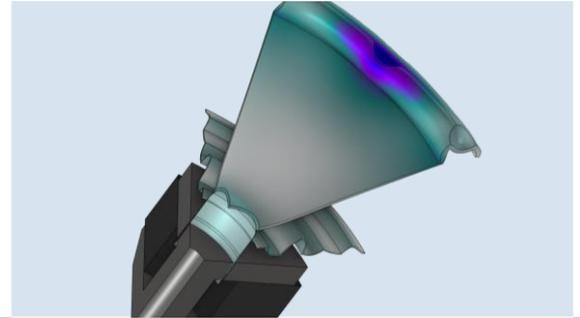
## High-Frequency BEM

- Solve scattering and radiation problems efficiently
- Acoustically large problems



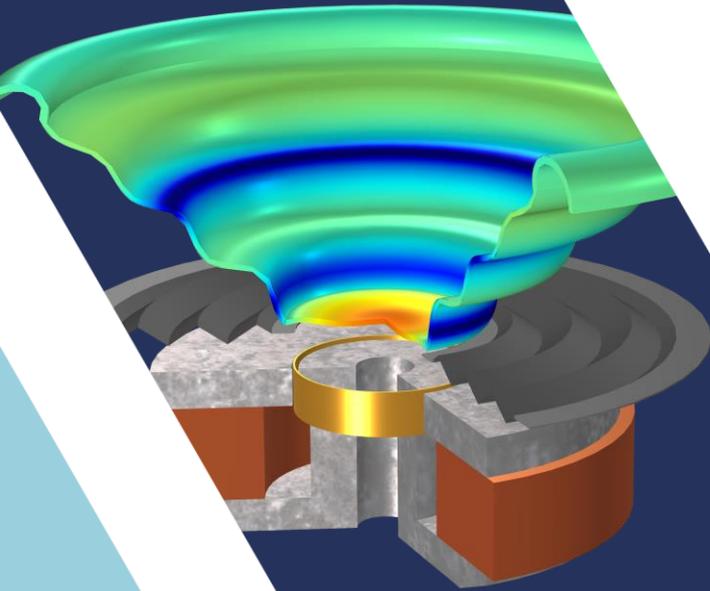
## Performance

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



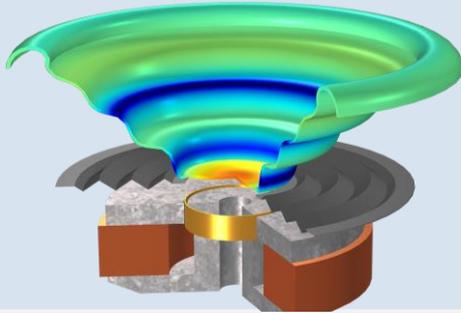
## Optimization

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



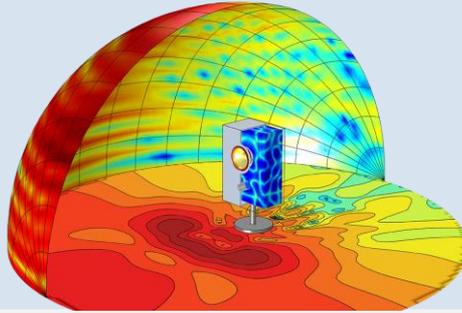
# Loudspeakers

# Analyses for Different Stages of the Development Cycle



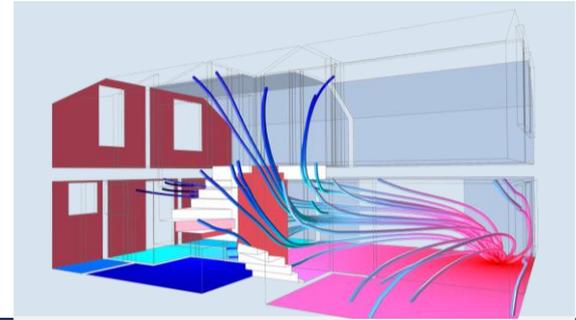
## Speaker Driver Design

- 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

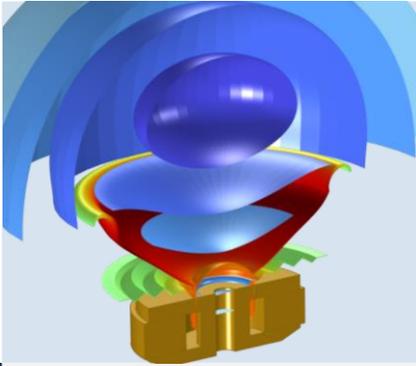
- Vibroacoustic analysis: *Pressure Acoustics*, *Frequency Domain* for the cabinet; *Pressure Acoustics*, *Boundary Elements* for the surrounding space; *Solid Mechanics* and *Shell* for the speaker components
- Frequency domain and eigenfrequency studies



## 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

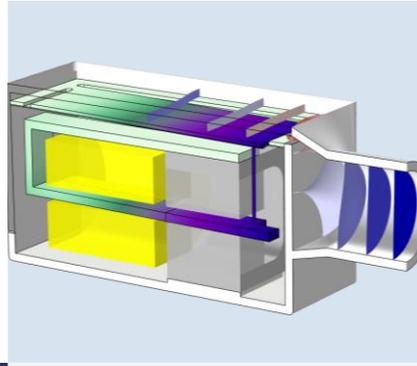
# Multiphysics Couplings for Different Types of Speaker Drivers



## Dynamic Moving Coil Transducers

Lorentz coupling

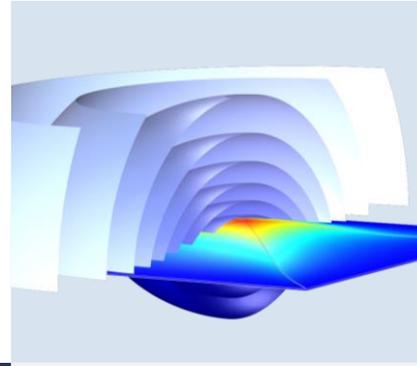
- *Magnetic Fields*
- *Solid Mechanics*



## Balanced Armature Receivers

Magnetomechanical forces

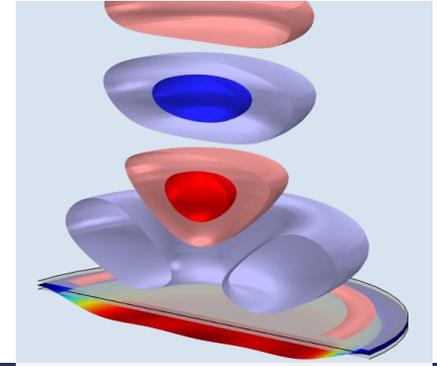
- *Magnetic Fields*
- *Solid Mechanics*



## Piezoelectric Drivers

Piezoelectric effects

- *Electrostatics*
- *Solid Mechanics*

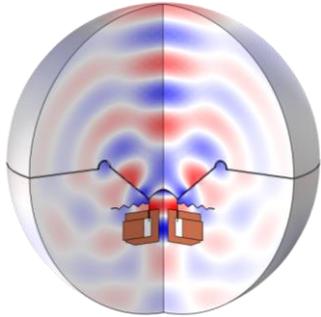


## Electrostatic Drivers

Electromechanical forces

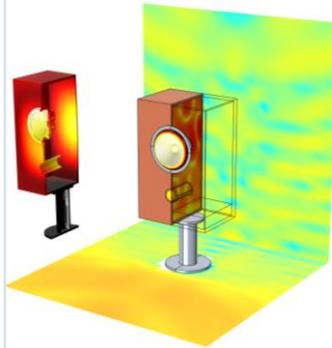
- *Electrostatics*
- *Solid Mechanics*

# Numerical Methods and Space Dimensions



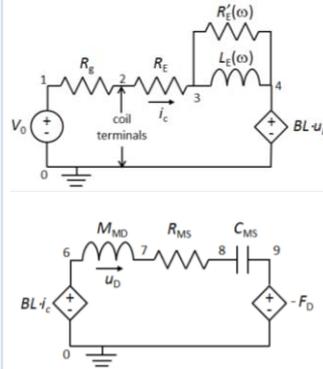
## Finite Element Method (FEM)

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



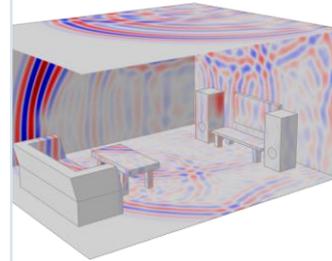
## Hybrid FEM-BEM

Space dimensions: 3D



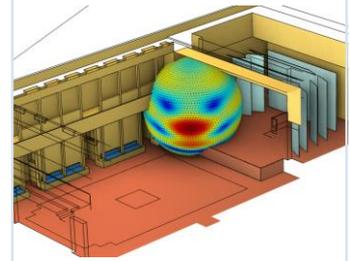
## Lumped Parameter

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.

balanced\_armature\_transducer\_60.mph - COMSOL

File Home Definitions Geometry Materials Physics Mesh Study Results Developer

Application Builder Model Manager Component 1 Add Component Parameters Variables Functions Variable Utilities Build All Import LiveLink Add Material Solid Mechanics Physics Build Mesh Mesh Solid Compute Study 3 - Mechanical Compliance

Model Builder

- balanced\_armature\_transducer\_60.mph (root)
  - Global Definitions
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Solid Mechanics (solid)
      - Pressure Acoustics, Frequency Domain (acpr)
        - Pressure Acoustics 1
        - Sound Hard Boundary (Wall) 1
        - Initial Values 1
        - Symmetry 1
        - Narrow Region Acoustics 1
        - Narrow Region Acoustics 2
        - Narrow Region Acoustics 3
        - Impedance 1 - Vent
        - Lumped Port 1 - Tube and Coupler
      - Magnetic Fields (mf)
        - Ampère's Law: Air Domain
        - Magnetic Insulation 1
        - Initial Values 1
        - Coil 1
          - Ampère's Law: Pole Piece
          - Ampère's Law: Permanent Magnet
          - Ampère's Law: Armature
          - Gauge Fixing for A-Field 1
      - Multiphysics
        - Acoustic-Structure Boundary 1 (asb1)
        - Magnetomechanical Forces 1 (mmf1)
    - Meshes
    - Study 1 - Frequency Response
      - Step 1: Coil Geometry Analysis
      - Step 2: Stationary
      - Step 3: Frequency Domain Perturbation
      - Solver Configurations
      - Job Configurations
    - Study 2 - Mechanical Modes
    - Study 3 - Mechanical Compliance
    - Results

Settings

Magnetomechanical Forces

Label: Magnetomechanical Forces 1

Name: mmf1

Domain Selection

Equation

Show equation assuming:  
Study 1 - Frequency Response, Coil Geometry Analysis

$$W_{EM} = W_s(C) + \frac{1}{2}(\mu_0 \mu_r I)^T C: (B \otimes B)$$

$$C = F^T F, \quad J = \det(F)$$

$$S = 2 \frac{\partial W_{EM}}{\partial C}, \quad H = \frac{\partial W_{EM}}{\partial B}$$

$$FSN \, dA = \sigma_{EM}^{(out)} \cdot n \, da$$

Coupled Interfaces

Solid mechanics:  
Solid Mechanics (solid)

Magnetic fields:  
Magnetic Fields (mf)

Graphics: Magnetic Field, Pressure, and Displacement

z  
y  
x

# 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.

The screenshot displays the COMSOL Multiphysics software interface for a model named 'loudspeaker\_driver\_transient.mph'. The top menu bar includes File, Home, Definitions, Geometry, Sketch, Materials, Physics, Mesh, Study, Results, and Developer. The toolbar contains icons for Application Builder, Model Manager, Component, Add Component, Parameters, Functions, Variable Utilities, Import, Build All, Add Material, Magnetic Fields, Add Physics, Build Mesh, Mesh, Compute, and Study 2 - Periodic Signal Extraction and F.

The **Model Builder** tree on the left shows the following structure:

- loudspeaker\_driver\_transient.mph (root)
  - Global Definitions
    - Parameters 1
    - Ramp 1 (rmt)
    - Interpolation 1 (p\_point)
    - Analytic 1 (p\_periodic)
    - Default Model Inputs
  - Materials
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Moving Mesh
      - Deforming Domain 1
        - Fixed Boundary 1
        - Prescribed Mesh Displacement 1
        - Symmetry/Roller 1
  - Component 2 (comp2)
    - Definitions
    - Global ODEs and DAEs (ge)
  - Study 1 - Time Dependent Analysis
    - Step 1: Stationary
    - Step 2: Time Dependent
    - Solver Configurations
    - Job Configurations
  - Study 2 - Periodic Signal Extraction and FFT
    - Step 1: Time Dependent
    - Step 2: Time to Frequency FFT
    - Solver Configurations
    - Job Configurations
  - Results

## 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.

The screenshot displays the COMSOL Multiphysics interface for a model named 'headphone\_artificial\_ear.mph'. The software is running in the 'Study' tab, showing a 3D model of a speaker driver in a headphone. The interface is divided into several panes:

- Model Builder:** Shows the hierarchical structure of the model, including Global Definitions, Component 1 (comp1), Electrical Circuit (cir), and Pressure Acoustics, Frequency Domain (acpr).
- Settings:** Shows the configuration for the 'Interior Lumped Speaker Boundary' condition. The boundary selection is set to 'Moving membrane'. The equation is set to 'Study 1 - Frequency domain, Frequency Domain'. The speaker area is set to 'Selected boundaries'. The speaker axis direction is set to 'User defined' with values (1, 0, 0) for (x, y, z).
- Equation:** Shows the governing equations for the speaker driver:
 
$$F_{ax} = \int (p_{t,down} - p_{t,up}) \mathbf{e}_{ax} \cdot \mathbf{n} dA$$

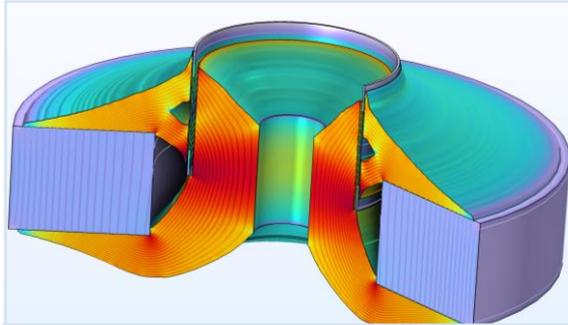
$$v_{ax} = i_{cir} [m/s/A]$$

$$v_{cir} = -F_{ax} [V/N]$$
- Circuit:** Shows the electrical circuit configuration, with the current source set to 'Current (cir/lvsU1)'. The frequency is set to 'freq=12500 Hz'.
- Graphics:** Shows a 3D visualization of the speaker driver in the headphone, with a color scale indicating pressure levels.

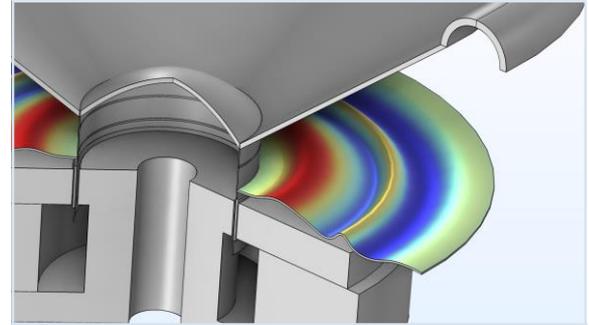
## EXAMPLES

# Optimization Analysis

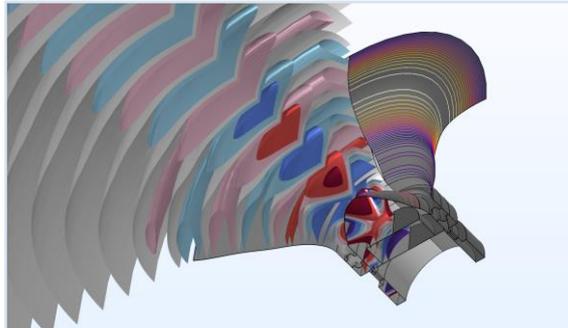
These tutorial models demonstrate how optimization methods can be used to design loudspeaker drivers and waveguides for the desired performance.



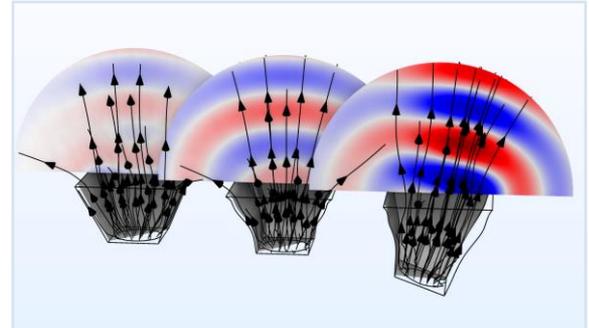
*Optimization of a magnetic circuit.*



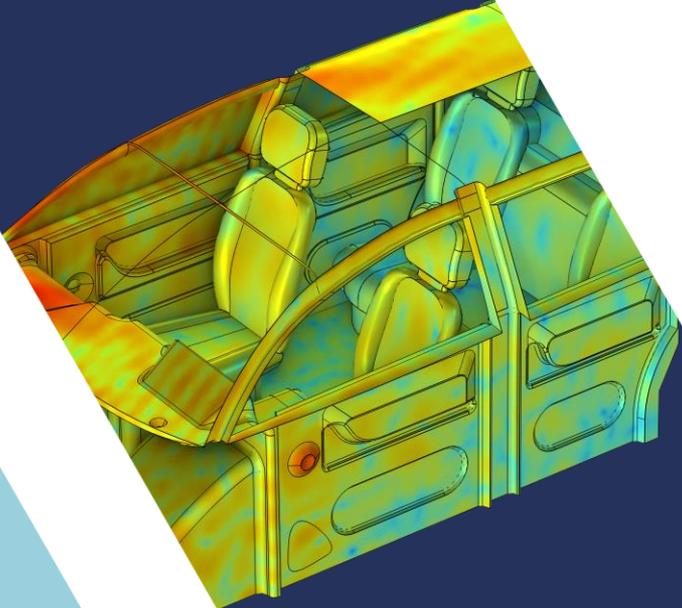
*Loudspeaker spider optimization.*



*Tweeter dome and waveguide shape optimization.*

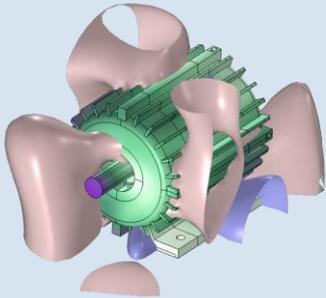


*Shape optimization of a rectangular loudspeaker horn in 3D.*



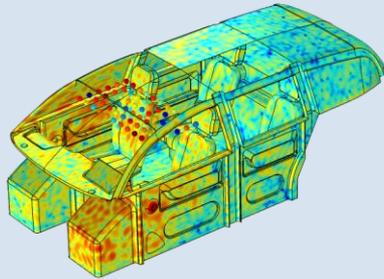
# Automotive Acoustics & NVH

# Automotive Acoustics Applications



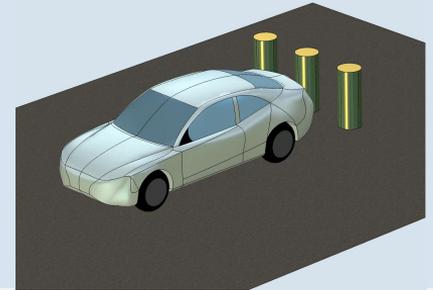
## Noise and Vibrations

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



## Car Cabin Acoustics

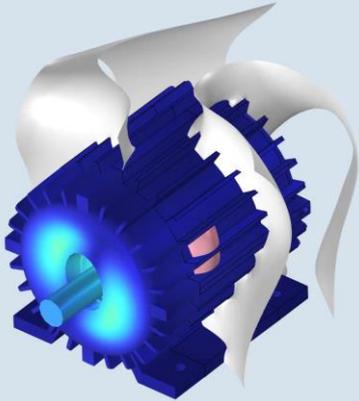
- Car cabin stereo
- Acoustic environment and personal sound zones



## Sensors

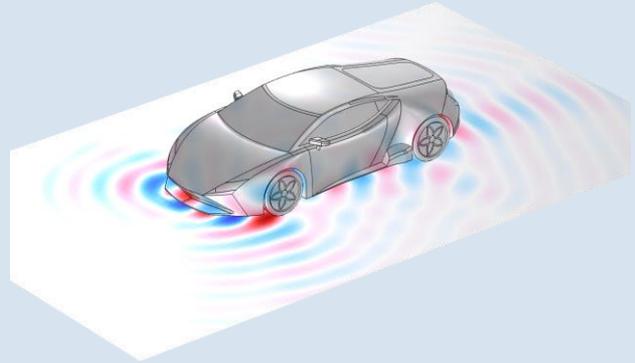
- Ultrasonic parking sensors
- Surface acoustic wave (SAW) tire pressure sensors

# Solutions for Automotive Acoustics



## Multiphysics

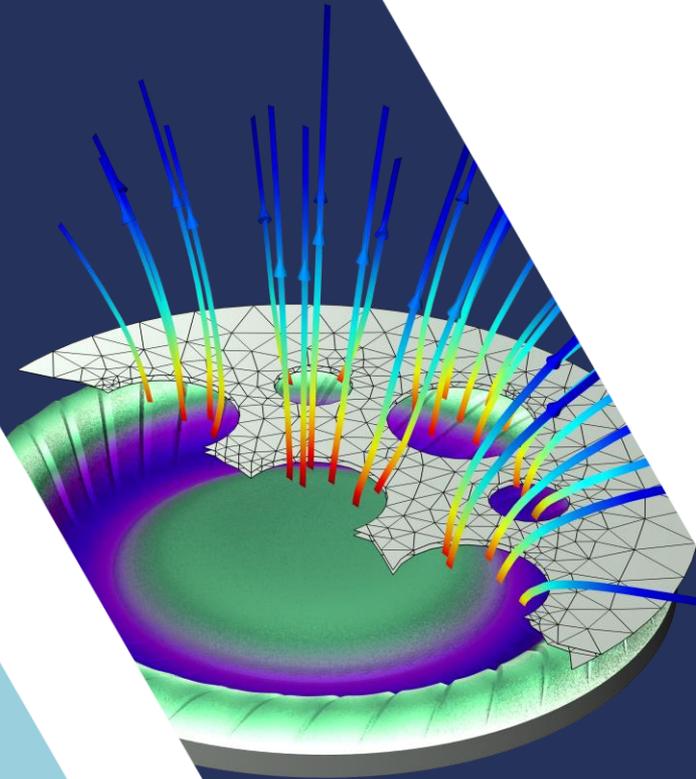
- Acoustic–structure interaction
- Porous materials
- Electroacoustics
- Piezoelectricity



## Multimethod

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

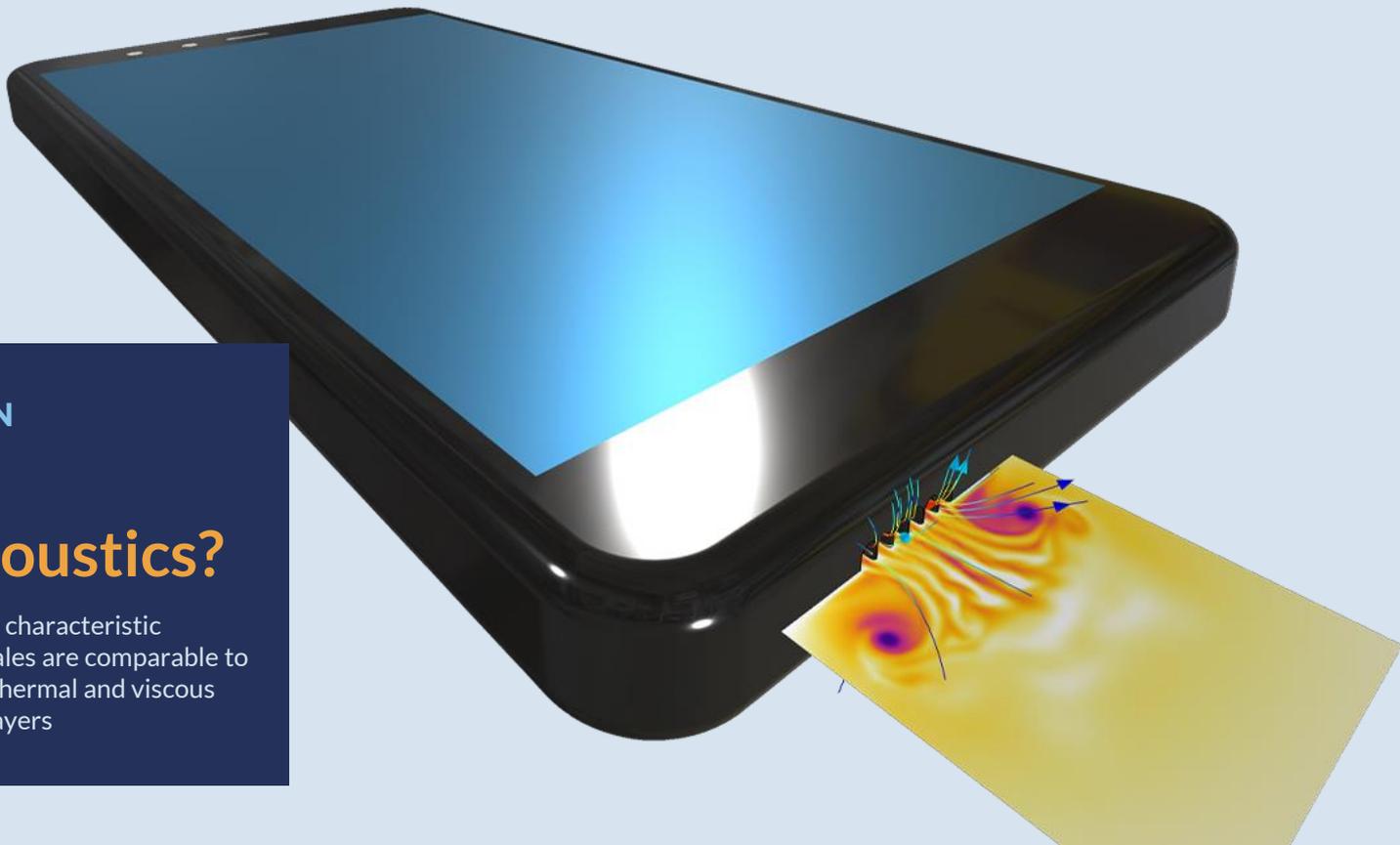
# Microacoustics



## 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

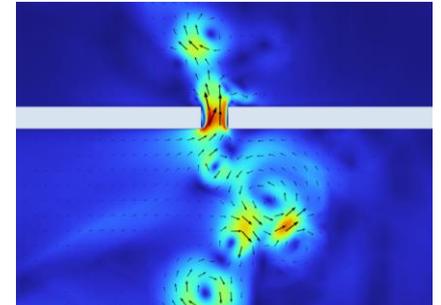
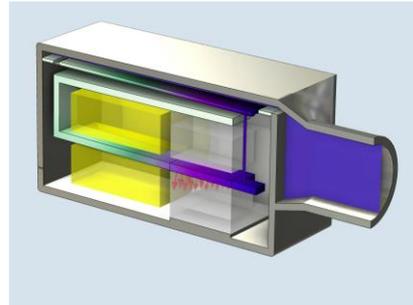
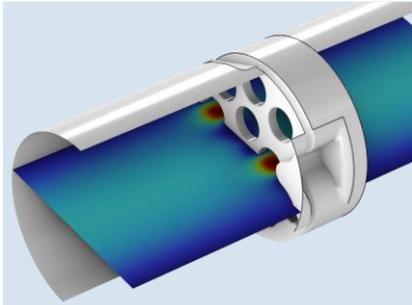
$$i\omega\rho_t + \nabla \cdot (\rho_0\mathbf{u}_t) = 0$$

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

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

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

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



## 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

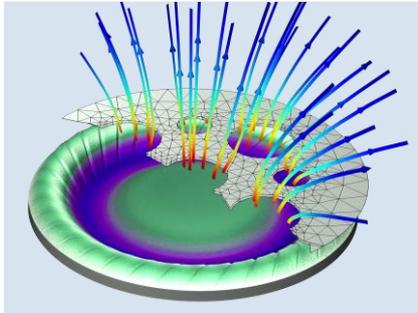
## Multiphysics

Coupling to structures and pressure acoustics for transducer modeling

## Nonlinear

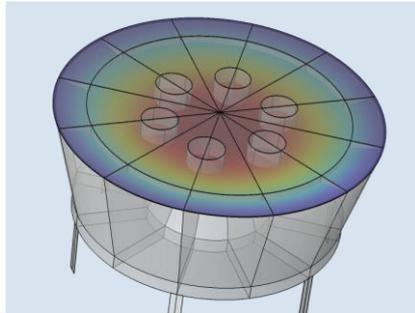
Nonlinear effects included in the time domain to model distortion and added resistive losses

# Thermoviscous Acoustic Applications



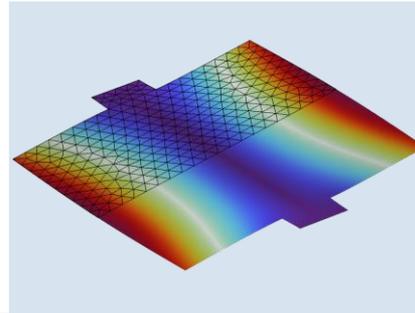
## Microspeakers

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



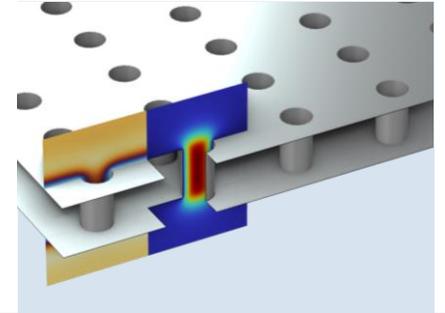
## Microphones

Microphones and their operation, as well as integration into devices



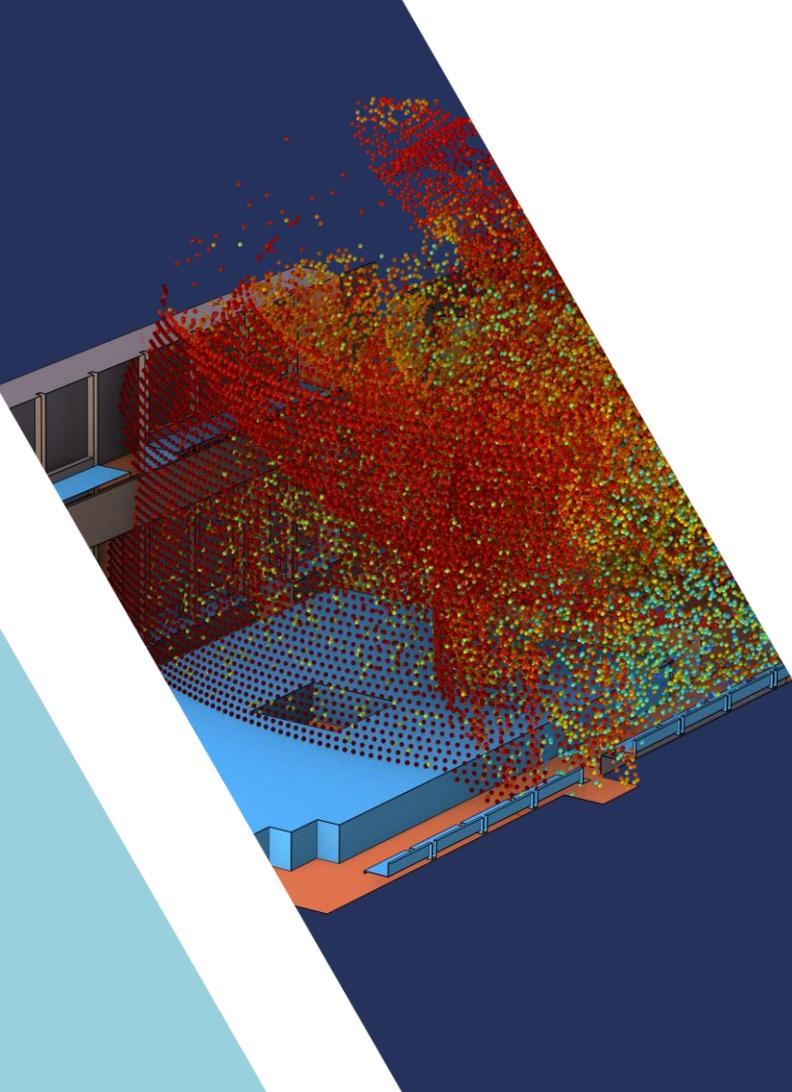
## MEMS

Operation of MEMS systems such as microphones and resonators



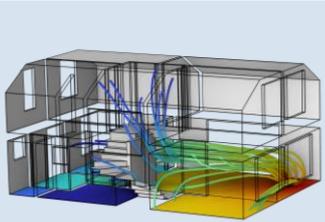
## Perforates

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



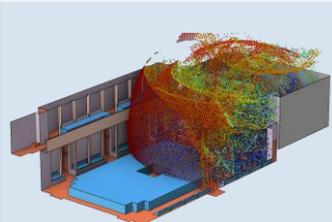
# Room Acoustics for Large & Small Volumes

# Acoustics Module Functionality



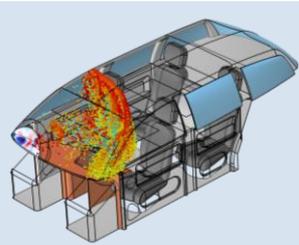
## Diffusion Equation

- Steady-state energy distribution
- Transient room energy decay



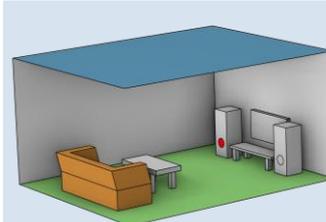
## Ray Acoustics

- Room impulse response
- Room acoustics metrics



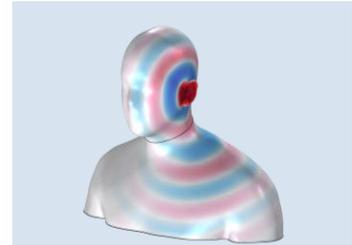
## Pressure Acoustics, Frequency Domain

- Submodels and coupling
- Modal analysis
- Room impulse response



## Pressure Acoustics, Time Explicit

Room impulse response



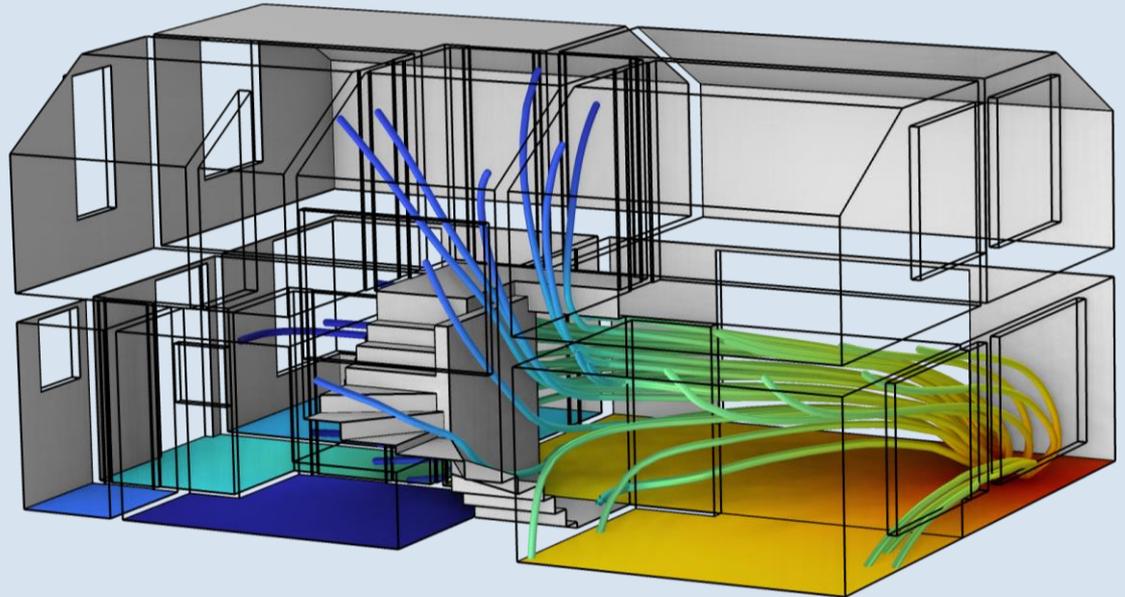
## Pressure Acoustics, Boundary Elements

Scattering problems

ACOUSTIC ENERGY

# Diffusion Equation

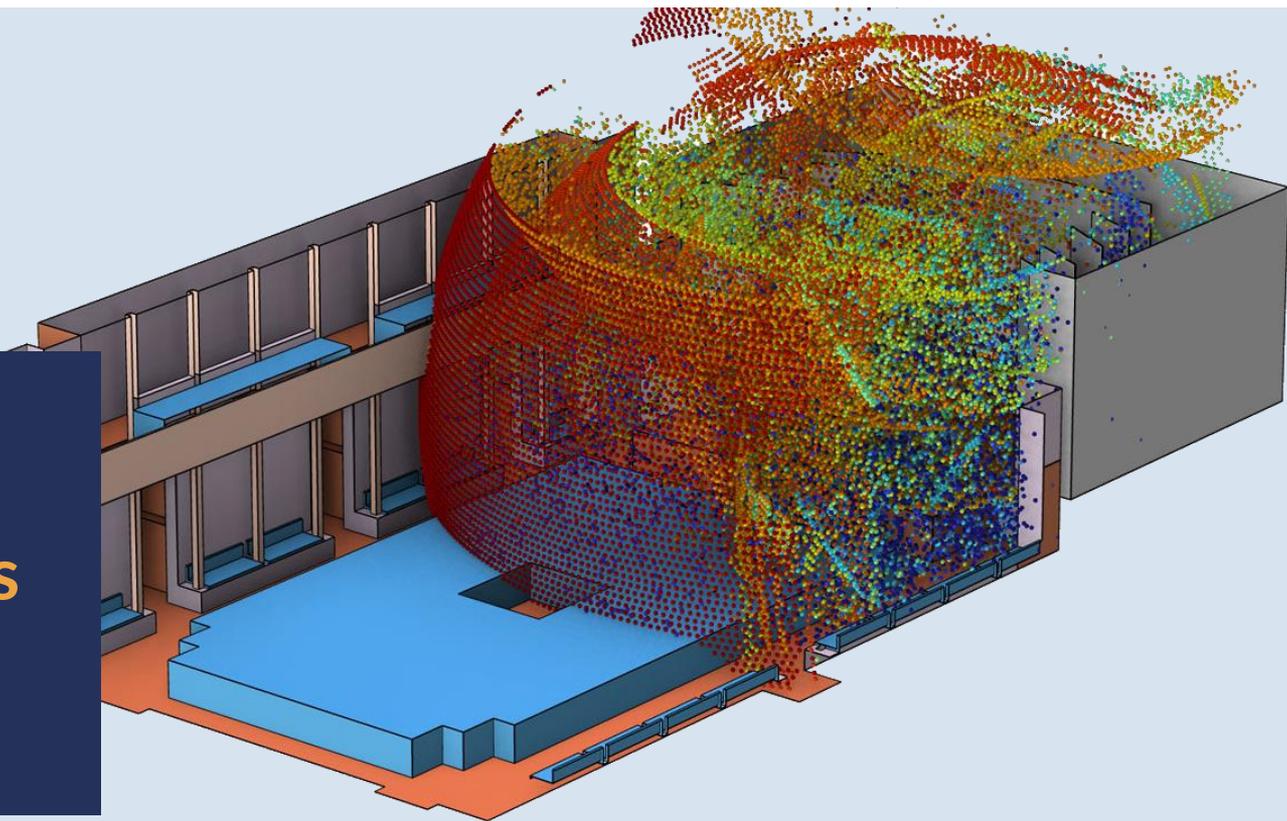
For broadband or octave band



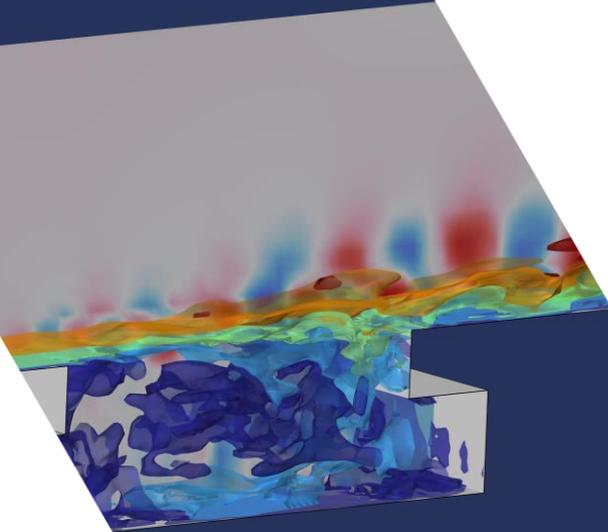
HIGH FREQUENCY

# Ray Acoustics

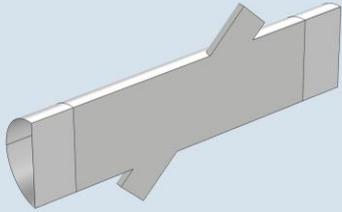
Intensity and power



# Aeroacoustics & Flow-Induced Noise

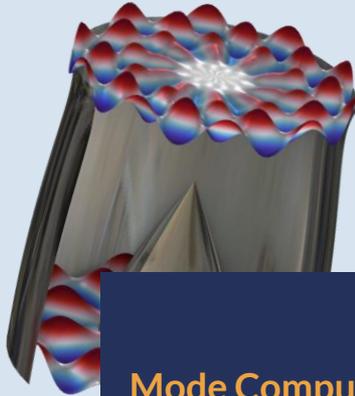


# Aeroacoustic Capabilities



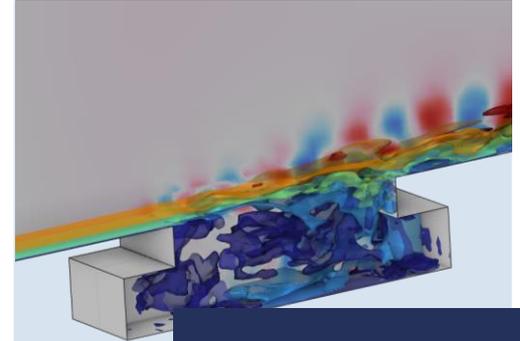
## Convected Acoustics

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



## Mode Computation

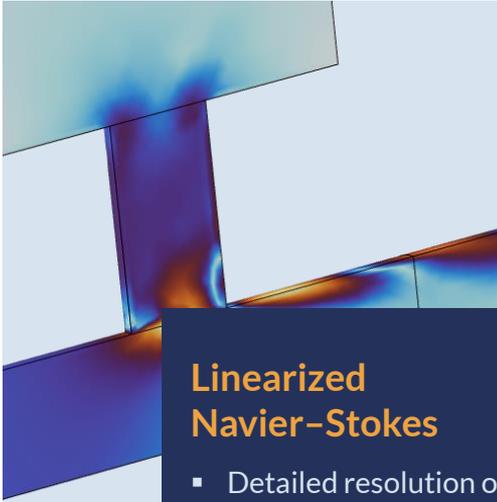
- Boundary mode interface to identify propagating and nonpropagating modes in ducts
- Essential for source characterization



## Flow-Induced Noise

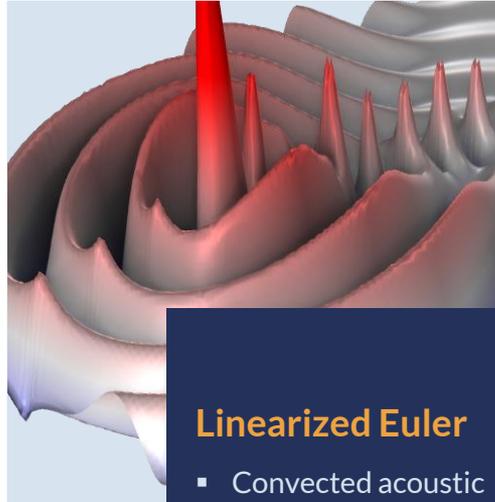
- Lighthill's acoustic analogy
- Acoustic wave equation (AWE)

# Convected Acoustics



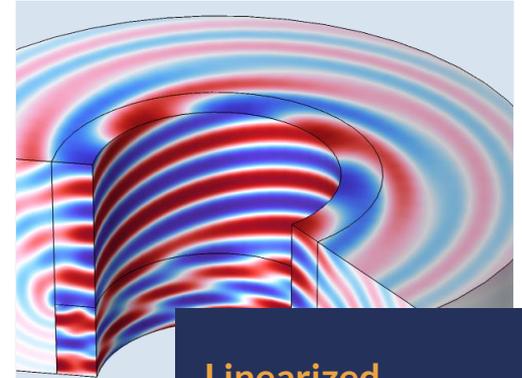
## Linearized Navier-Stokes

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



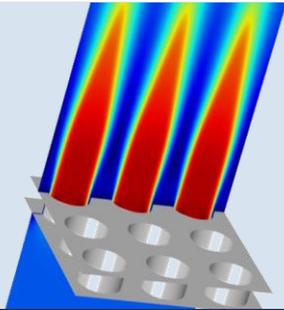
## Linearized Euler

- 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

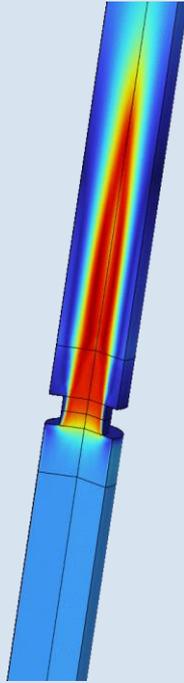


## SUBMODELING

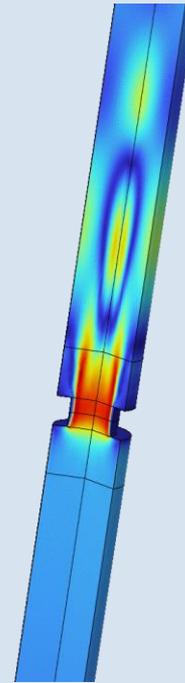
# Transfer Impedance of Perforate with Bias Flow

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

$f = 500$  Hz

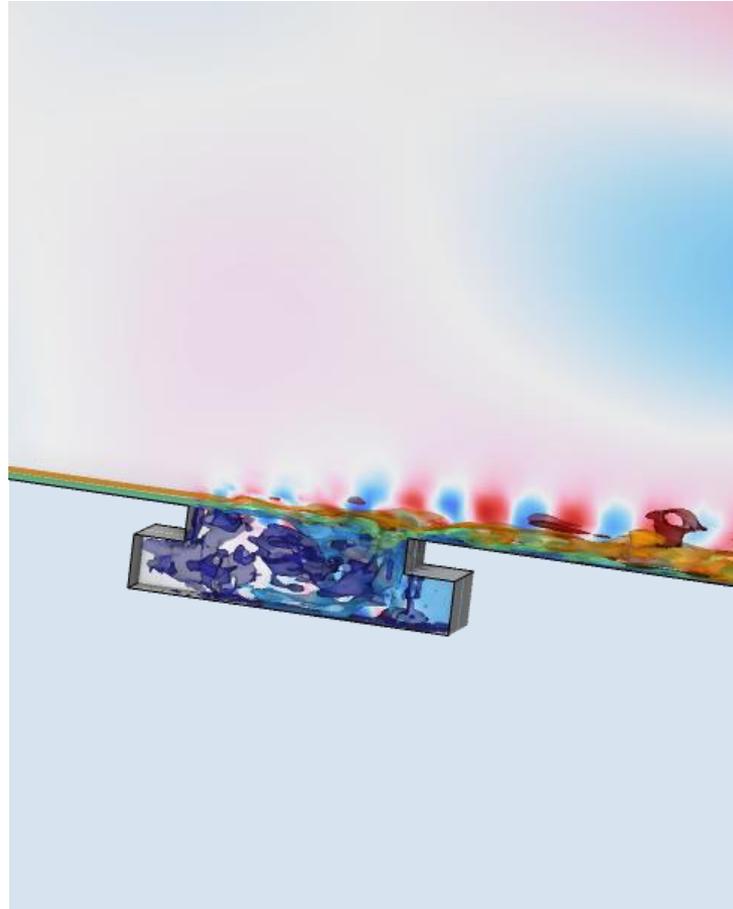


$f = 5000$  Hz



# 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

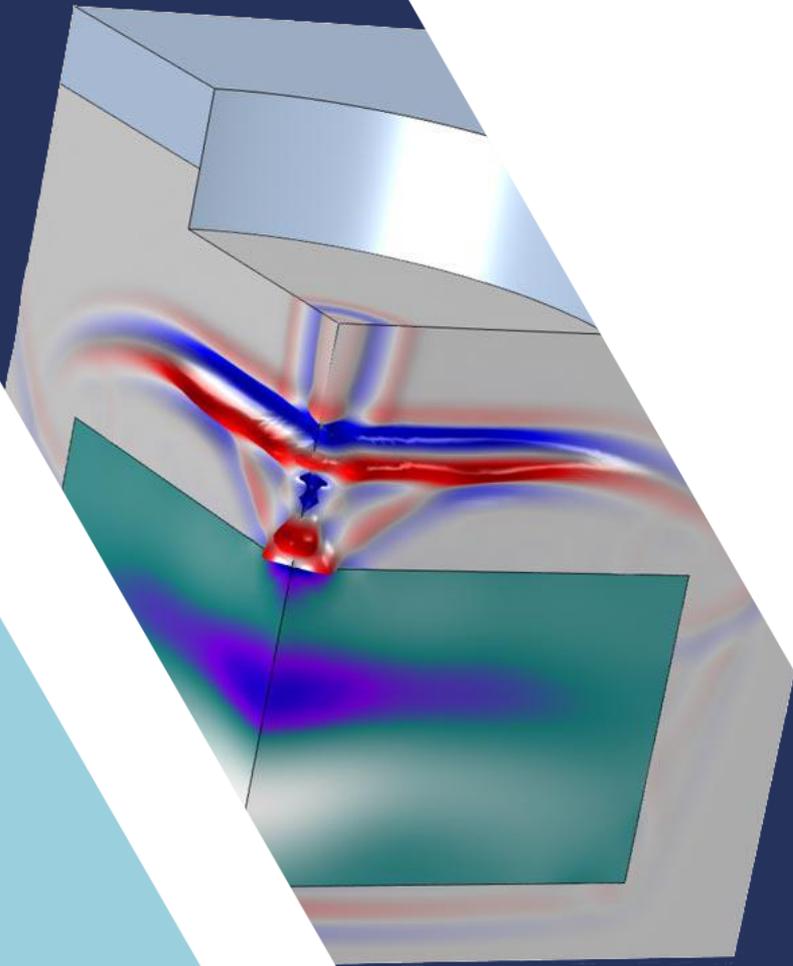


## Resolve Time and Space

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

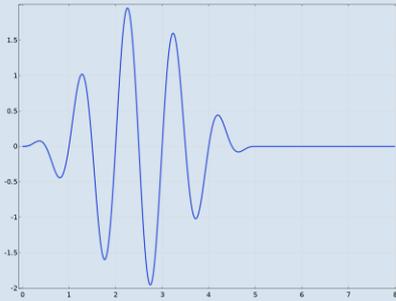
## Computational Effort

LES simulations require good computational resources.



# Ultrasound & Nondestructive Testing

# Modeling Ultrasonic Wave Propagation in the Time Domain



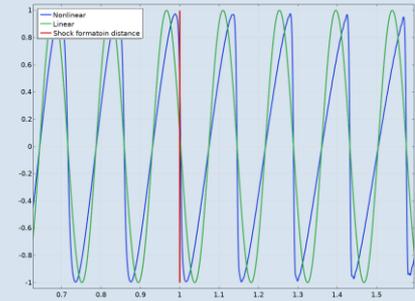
## Signal Type

- Pulses
- Modulated sinusoidal signals



## Operating Principle

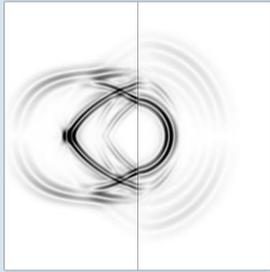
- Sonic reflection (pulse-echo) measurement
- Time of flight computation



## Nonlinear Effects

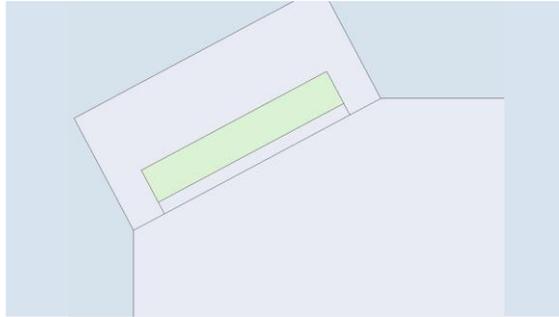
- High harmonic generation
- Shock waves

# Physics Interfaces for Modeling Ultrasound



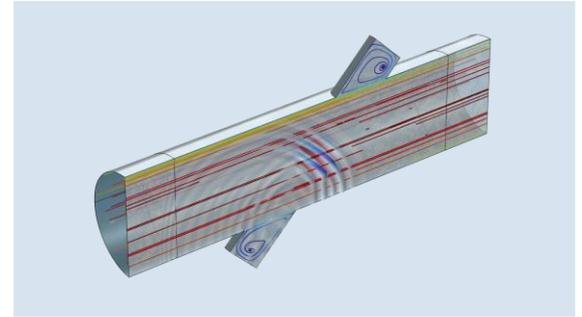
## Linear Elastic Solids

*Elastic Waves, Time Explicit*



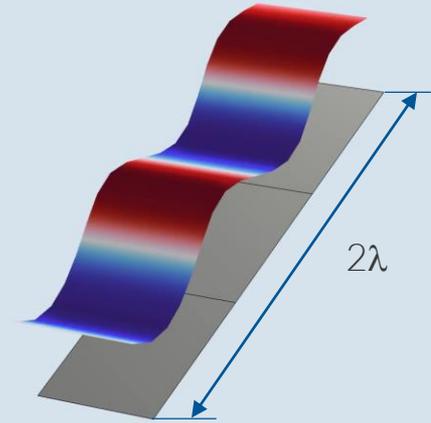
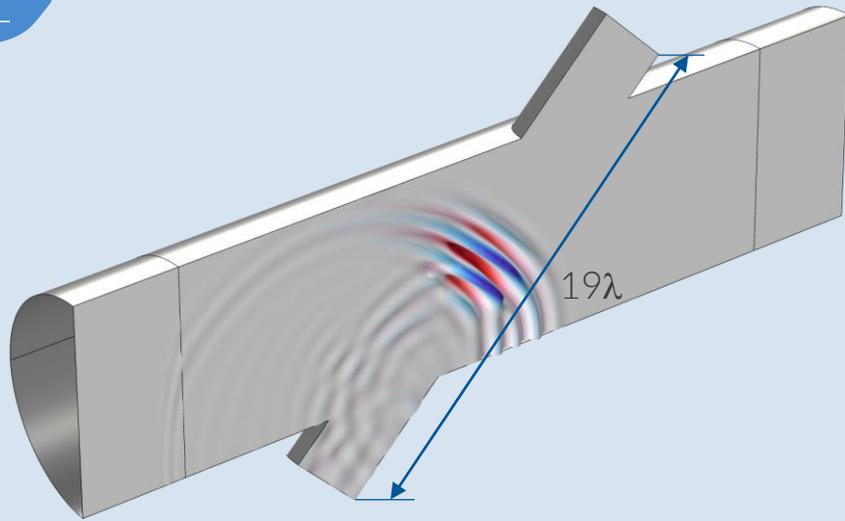
## Piezoelectric Solids

*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)

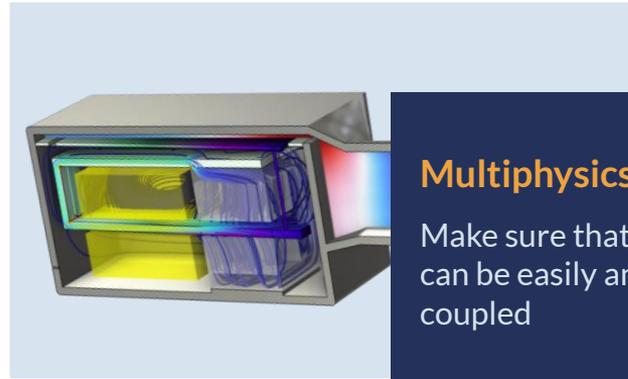
- Suited to acoustically large problems ( $L \gg \lambda$ )
- Uses higher-order discretization (4<sup>th</sup> order by default)
- Memory lean and high-performance computing (HPC) enabled

# The COMSOL® Software Is the Right Tool for the Job



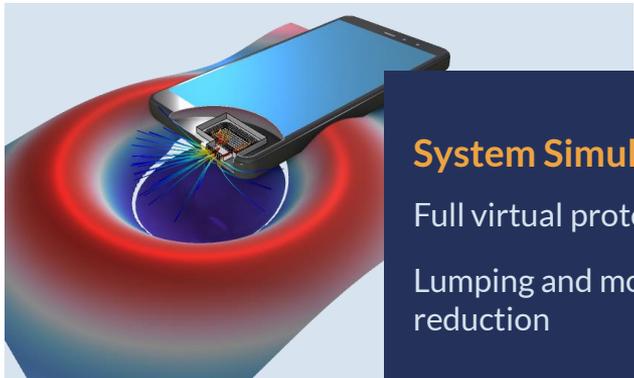
## Multimethod

Combine and use the strength of different numerical methods



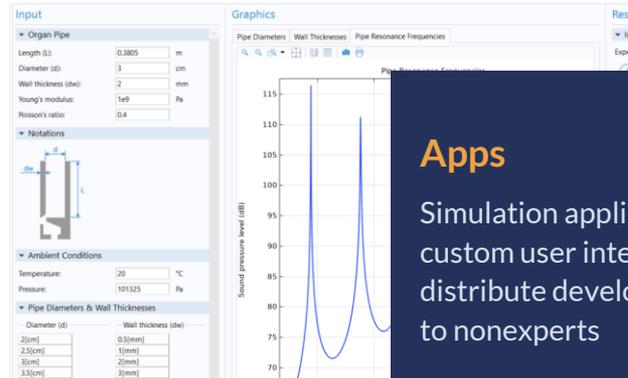
## Multiphysics

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