Application for Simulating Acoustic Response of Condenser Microphone Cartridges

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Abstract

Electret condenser microphones are one of the most used transducers for a variety of applications. An FEM simulation with representative geometry has several advantages over a traditional lumped element equivalent circuit simulation of such a transducer. This simulator application allows dimensions and parameters to be input directly, creating the model instead of having to dissect a design, create an equivalent circuit and take those inputs into equations to determine equivalent circuit component values. It allows for the electrical, mechanical, and acoustical aspects of a design to output a frequency response, polar response, cartridge capacitance and static diaphragm deflection distance. The cartridge characteristics are specified by entering dimensions for ports, cavities, and the housing of the cartridge and electrical, mechanical, and acoustical parameters, such as polarizing voltage, diaphragm resonance frequency, and acoustical resistance. The user can select the acoustic source used in the model including the frequency range, distance, and angle(s) of incidence.

Keywords: Microphone, Transducer, Condenser, Frequency Response, Diaphragm, Application Builder

Introduction

Condenser microphones are one of the most used transducers for a variety of applications, including speech, vocal, and instrument sound capture. These transducers have a construction like that of a parallel plate capacitor, but with one of the two plates being a moveable diaphragm that responds to incoming sound pressure waves and the other a stationary backplate. With an initial spacing between the diaphragm and backplate x_0 and a fixed charge on the backplate E, any induced diaphragm movement will result in an electrical signal output equal to $e = E * \Delta x / x_0$.

This movement of the diaphragm as a response to a given sound wave, creating a change in the spacing Δx, is determined by a complex mechano-acoustic system made up of the parts identified in this report. The diaphragm movement for directional microphones is the difference between the pressure at the front and back of diaphragm, which is tuned through the acoustical network.

There are certainly assumptions being made with every simulation, but a FEM simulation with representative geometry has advantages over a traditional lumped element equivalent circuit simulation of a transducer. The simulator allows dimensions and parameters to be input directly, creating the model instead of having to dissect a design, create an equivalent circuit and take those inputs into equations to determine equivalent circuit component values. Lumped elements also inherently carry more assumptions, including frequency limitations within the audio band for a given size, which can result in a less accurate model.

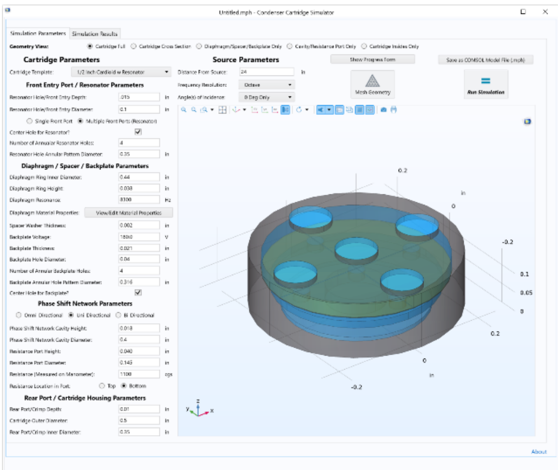


Figure 1: Application Main Screen showing Parameters and Geometry of the Cartridge

The model for a Brüel & Kjær 4134 Condenser Microphone from COMSOL’s Application Library (Application ID: 12375) was used as a reference in the development of this application [1]. While this sample model showed a measurement microphone, the application was built with the intent of designing microphone cartridges for sound reinforcement, thus requiring the ability to simulate directional cartridges. For directionality, a condenser cartridge must have two entry ports and account for the phase difference of a given input sound wave between those two ports.

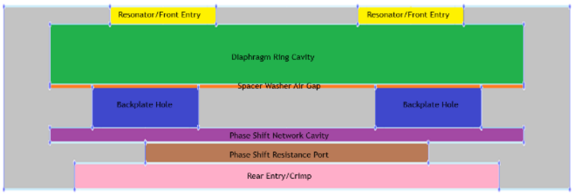
Application Overview

Geometry Input

The application as depicted in Figure 1 has two main screens, identified as “Simulation Parameters” and “Simulation Results” in the top left-hand corner of the screen. A drop-down menu at the top left corner labeled "Cartridge Template" includes options of generic designs to highlight the application. The initial design default is a half-inch diameter cartridge with a Cardioid polar pattern, a prototype of which was built and tested to serve as initial validation of the simulator.

At the top of the screen, an array of radio buttons allows the user to select different ways to view the geometry to better see what the input dimensions have created in the model. A cross-section view is available as well as views removing certain parts.

Cartridge Geometry Overview



Gray – Cartridge Housing	Green – Diaphragm Ring Cavity	Blue – Backplate Holes	Brown – Resistance Port
Yellow – Front Entry / Resonator	Orange – Spacer Washer	Purple – Phase Shift Cavity	Pink – Rear Entry / Crimp

Figure 2: Diagram of the Geometry Modeled in the Simulation

The simulator is constrained to a cartridge design that is made up of a stackup of cylinders of air whose locations are fixed relative to each other. For the simulation, the air is what is simulated which results in the simulation geometry to appear like a negative of the physical parts in the assembly. The diaphragm is the only aspect modeled in this simulation that is not effectively a container of air.

While there are certainly other ways to design a condenser cartridge, this template is seen in many designs and is easy to generalize. The cartridge contains, from top to bottom, an Entry Port or Resonator, a Diaphragm, a Spacer Washer, a Backplate, a Phase Shift Network made up of a cavity and a resistance port, and a rear port. All these parts are contained within a cartridge housing and a container of air around the housing. For an Omni-Directional cartridge design, the Rear Entry and Resistance Port are removed as only one entry is needed. The total height of the cartridge is the combination of the heights of all these parts. These sections of the design show the air that is contained within physical parts of an actual design. While typically hidden from view in the model, the entire cartridge is surrounded by a bounding cylinder of air allowing a simulated wavefront to move in and around the cartridge.

Editable Parameters

First for the front entry, the depth of the hole(s) and diameter of the hole(s) can be specified. Then the user can decide between a single front entry acoustic port, or a multi-entry acoustic port network labeled "Resonator." If the latter option is selected, the user can use a check box indicating whether a hole is placed at the center of the resonator. Finally, the number of annular holes and their distance from the center can be specified. Specifying the hole pattern in this way is a bit limiting, but still allows for flexibility and will result in a simple part that can be easily manufactured.

The microphone diaphragm's construction is assumed to be a tensioned membrane attached to a circular ring. The height and inner diameter of that ring are included as editable parameters. While the tension of the diaphragm is the parameter that affects microphone response, it is typically measured as a resonance frequency in a production setting and thus, that value is an assignable parameter and tension is calculated back with the help of other geometric and material parameter inputs. The user can input the following material parameters for the diaphragm membrane: thickness, mass per unit area (density), Young's modulus, and Poisson's ratio.

The spacer washer's thickness creates the gap between the backplate and diaphragm and the initial spacing x_0. It is assumed that the inner diameter of the spacer washer, diaphragm ring, and backplate are all equal, creating an air gap out of a single cylinder of air.

The geometry of the backplate can be entered in with the same options as the front entry port. These parameters include the thickness of the backplate, the number of holes, the hole diameter, as well as the distance of the holes from the center. There is a check box indicating whether there is a hole in the center of the backplate. The voltage applied to the backplate E is also input as a parameter. This simulation uses a simple bias circuit through the Circuit physics to apply this voltage to the backplate. While it is common for these transducers to use an electret layer on the backplate to create this fixed charge, there is not a difference in the results compared to modeling it as an external circuit bias.

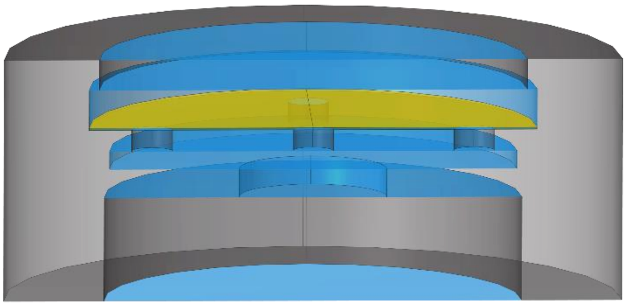


Figure 3: Sample Geometry View with Diaphragm Highlighted in Yellow, Bounded Air in Blue, Cartridge Housing in Black

The cartridge's phase shift network contains both an acoustic cavity and a resistance port that allows for cartridge to have a uni-directional polar pattern. For an omni-directional design, only the cavity is used, and the resistance port is removed.

The cavity is directly above the resistance port and this simulator allows the user to place a resistance on either the top or bottom surface of the resistance port. When selecting the bottom location in the port, the user is effectively creating an enclosed volume combining the cavity and resistance port volumes. The height and diameters of both components can be specified, and the resistance value is entered in units of cgs acoustic ohms (cgs Rayls measured over a one cm^2 area, base units of g/(cm^4 ·s)). For a bi-directional cartridge, the phase shift resistance is automatically set to zero as they are not tuned with this parameter.

The final geometry inputs set the housing that the cartridge is contained in. The rear port, which is often through the middle of a crimped edge or closing piece to hold the parts in, is specified with a height and diameter. The outer diameter of the cartridge housing is also specified, which effectively allows the user to account for its wall thickness. The height of the cartridge is fixed as the summed total height of all the components specified.

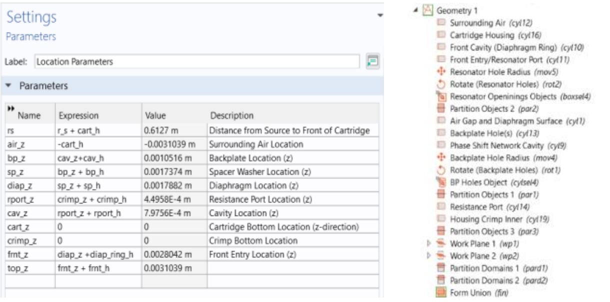
The remaining inputs to the simulation are accessible in the top middle of the screen. The user can specify the parameters of the source including its distance away from the cartridge, the frequency resolution, and the angles of incidence. There are multiple options for the frequency resolution and incidence angles that allow the user to dramatically change the time it takes the simulation to run as a trade off with more data points. Selecting "Polar Plot" as the incidence angle will then simulate at 5˚ increments up to 180˚ and assume symmetry.

There are three more buttons on the parameters screen, one that shows the mesh in the graphics window, one that will begin the simulation and one allowing the user to reopen a popup screen with the simulation progress. The mesh is automatically generated when the simulation runs, but the "Mesh Geometry" button allows the user to view the mesh prior to running. The progress screen shows the number of degrees of freedom solved for, the status of each step the solver is taking and a progress bar showing the portion that is complete.

Model Setup

Parametrized Geometry

The usability of this simulation tool relies heavily on the parameterization of geometry that can be done in COMSOL. Having all important geometric parameters editable to the user and interconnected is crucial to the function of this application.


Settings
Parameters
Label: Location Parameters
Parameters

Name	Expression	Value	Description
rs	r_s + cart_h	0.6127 m	Distance from Source to Front of Cartridge
air_z	-cart_h	-0.0031039 m	Surrounding Air Location
bp_z	cav_z+cav_h	0.0010516 m	Backplate Location (z)
sp_z	bp_z + bp_h	0.0017374 m	Spacer Washer Location (z)
diap_z	sp_z + sp_h	0.0017882 m	Diaphragm Location (z)
rport_z	crimp_z + crimp_h	4.4958E-4 m	Resistance Port Location (z)
cav_z	rport_z + rport_h	7.9756E-4 m	Cavity Location (z)
cart_z	0	0	Cartridge Bottom Location (z-direction)
crimp_z	0	0	Crimp Bottom Location
fmt_z	diap_z +diap_ring_h	0.0028042 m	Front Entry Location (z)
top_z	fmt_z + fmt_h	0.0031039 m	

Geometry 1
Surrounding Air (cyl12)
Cartridge Housing (cyl16)
Front Cavity (Diaphragm Ring) (cyl10)
Front Entry/Resonator Port (cyl11)
Resonator Hole Radius (mov5)
Rotate (Resonator Holes) (rot2)
Resonator Openinings Objects (boxsel4)
Partition Objects 2 (par2)
Air Gap and Diaphragm Surface (cyl1)
Backplate Hole(s) (cyl13)
Phase Shift Network Cavity (cyl9)
Backplate Hole Radius (mov4)
Rotate (Backplate Holes) (rot1)
BP Holes Object (cylsel4)
Partition Objects 1 (par1)
Resistance Port (cyl14)
Housing Crimp Inner (cyl19)
Partition Objects 3 (par3)
Work Plane 1 (wp1)
Work Plane 2 (wp2)
Partition Domains 1 (pard1)
Partition Domains 2 (pard2)
Form Union (fin)

Figure 4: Geometry Location Parameters and List of Objects

Starting with the cartridge housing and rear port, the location of each part is expressed as a function of other parts heights and locations in a layout indicated in Figure 2. All objects are cylinders that represent the contained volumes of air, with some being moved, copied, and rotated according to user input. The holes for resonators or backplates are created as a single cylinder object first. Then a move command and a rotate command place those holes in their location based on what is specified. To create the edges used for viewing the diaphragm displacement, the air gap domain was partitioned along both the x and y axes. A cylinder of air surrounding the cartridge is created, and layers are added to be used as Perfectly Matched Layers, which allows for a background pressure field source as well as diffraction to be considered and for reflections from the air boundary to be eliminated.

In addition to creating the geometry, selections must be made from that geometry to properly apply physics and update when it changes. COMSOL allows for selections to be made based off of parameter values so as the domain numbering changes, the selections will stay as intended. For example, the highlighted surfaces in Figure 5 will be used to set the walls in the backplate. As the user may change the number of backplate holes or their size, the selection will remain the same as it is constrained using the diameter and height of the backplate according to the parameters.

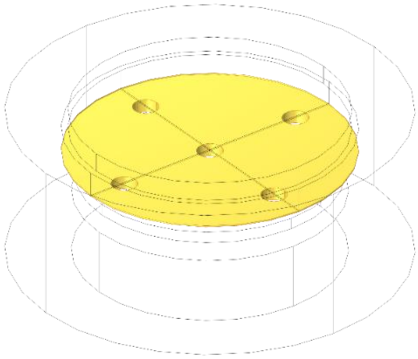


Figure 5: Backplate and Air Gap Wall Selection Created from Parameters

On all parts of the geometry, a material must be selected. For this model, the only materials that needed to be specified are air and the diaphragm material. The air selection goes to all of the domains in the model and the diaphragm material is applied only to the diaphragm face selection. The properties of this material are parameterized and thus will change with the users input in the application window.

Applied Physics and Multiphysics Couplings

The physics used in this model are based off an example model of a Brüel & Kjær 4134 Condenser Microphone that was provided by COMSOL. Thermoviscous Acoustics, Electrostatics, Membrane, and the Moving Mesh were all utilized in this simulation reference and this application incorporated Pressure Acoustics and Electrical Circuit physics into the model as well.

Thermoviscous Acoustics, Frequency Domain physics is applied to the air gap domain as well as the air inside the holes of the backplate. This set of physics will consider the pressure, temperature, and velocity using the linearized Navier-Stokes equations and is particularly useful to model damping in small areas [2]. The acoustical damping created by the thin air gap between the diaphragm and backplate often has a large effect on the frequency response of a condenser cartridge and is difficult to simulate with lumped elements due to its non-trivial dependence on the geometry of the air gap. The only boundary conditions applied are to the walls, which have a condition of zero velocity.

Pressure Acoustics, Frequency Domain physics is used for all the other air in the model, where thermal losses are not the driving factor for the acoustical design. Pressure is the only variable solved for using the Helmholtz Equation, needing significantly less solve time than Thermoviscous Acoustics [3]. Boundary conditions applied include two separate Sound Hard Boundary conditions for walls inside and outside the cartridge and an impedance condition to represent the acoustic resistance in the phase shift network. A background pressure field condition on the surrounding air domain is set to have a spherical wave incident from the distance and angle specified in the parameters. This is crucial to simulate the directionality of the cartridge as the polar pattern is tuned in the phase shift network relative to the front to back difference in phase of the sound waves. The source amplitude is also specified, but currently hidden from the user. The default pressure amplitude is 1 Pa (94 dB SPL), a common reference level used in microphone testing. The perfectly matched layers are specified in this physics step and identified as PMLs in the Artificial Domains definitions.

Membrane physics is applied to the diaphragm surface. The boundary conditions of tension (via the Linear Elastic Material, Initial Stress and Strain condition), thickness, and Electrostatic force load that couples with the Electrostatic physics are applied to the entire diaphragm surface. This force is used to set the initial condition of displacement of the diaphragm. A fixed condition around the diaphragm edges is also set.

Electrostatics physics is applied to the entire air gap domain with the top area of the backplate (excluding the hole open areas) as a terminal and the diaphragm as the ground. That terminal is connected to the Electrical Circuit physics interface which has components that establish the charge on the backplate. A fixed DC voltage source of the backplate voltage level set by the user is connected through a 10 MΩ resistor to the backplate terminal, which will generate the electric field. This electrical setup assumes there are no losses due to stray capacitances that would be present in a real design. However, this assumption will only influence the sensitivity of the microphone not its frequency response.

Three Multiphysics couplings are defined in this model, coupling the two acoustics physics with the membrane physics. The couplings of the Thermoviscous Acoustics to the Membrane and the Pressure Acoustics to the Membrane are located on the diaphragm boundary. The coupling of the Pressure Acoustics to the Thermoviscous Acoustics occurs are the bottom of the backplate holes.

Meshing and Study Setup

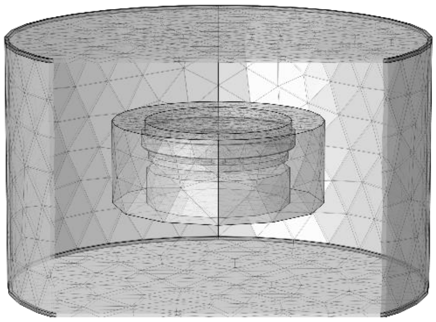


Figure 4: Cross Section View of Full Meshed Geometry

In addition to the physics, the meshing of the geometry is also set by the parameterized selections so that when features like holes are added or removed, the model is still properly setup. A vast majority of the model utilizes a Free Tetrahedral Mesh with the maximum element size parameterized to give six elements per wavelength at the specified maximum frequency of 15 kHz. Currently these parameters are not changeable by the user in the application but are parameterized within the model.

To accurately simulate the narrow region of the backplate/diaphragm air gap, the diaphragm surface is meshed with a Free Triangular mesh and this mesh is swept through the air gap with a seven elements thickness. The Perfectly Matched Layers are also meshed using a Swept mesh. A boundary layer mesh is applied near the edges of the backplate holes as well to help improve the accuracy of the losses in the Thermoviscous Acoustics physics.

In this model, there are four studies that are defined, three of which are used in the application currently. Study 1 uses an Eigenfrequency step to simulate the resonance frequency of the tensioned membrane. This study was used to validate the resonance frequency parameter to tension conversion. Studies 2-4 produces the output that is displayed in the simulator. Study 2 is actively altered by the input parameters in the application while the other two are set as defaults for ease of use within the model.

Each of these studies contain two steps, Stationary and Frequency Domain Perturbation. The former solves for the initial condition of diaphragm displacement due to the electrostatic force pulling it towards the backplate. The latter step sweeps through user selected frequencies in the Pressure Acoustics Background Pressure Field step as the field was set with the *linper()* operator (as seen in the example B&K model). To vary the incidence angles, a study extension is setup for each frequency to alter the parameter ‘th’ which is used in the source.

Results and Plotting

The output of these simulator is setup in the Results portion of the COMSOL model. There are various auto-generated plots from the study steps, but the main outputs are the Frequency Response, Polar Response, Diaphragm Displacement and Capacitance. The response of the microphone is expressed as “20*log10(abs(es.V0_1/pin))” where the parameter *pin* is the specified source pressure amplitude and *es.V0_1* is the small signal AC voltage level present at the backplate. The Diaphragm Displacement graph uses line graphs of the variable *wm*, the membrane’s displacement in the z-direction, over a line directly through the diaphragm on both the x and y axes. The theoretical collapse limit is plotted along this line as well. The Capacitance of the cartridge is calculated using “es.Q0_1/es.V0_1” which is the definition of capacitance, charge per voltage, measured at the backplate terminal.

The report feature of COMSOL creates a document with all the information specified from the simulation. This report is saved as Word Document (.docx) and contains three sections: Parameters, Geometry & Mesh, and Study & Results. The parameters are presented in tables, including calculated values not visible in the GUI. The Geometry & Mesh section shows the selections of each part, allowing the user to better see what exactly the geometry looked like, and the Study & Results section has plots and tables of all the output data that was viewable in application.

Output And Results

Results Screen

After completing the simulation, the second program screen will update and can be accessed by pressing the tab in the top lefthand corner of the screen. The “Simulation Results” screen contains a large graphics window to view results and buttons to select which to view. The “Plot Selection” array of radio buttons allows the user to select which output is displayed on the large graphics window. The three options are “Frequency Response” which will display the microphone’s output in dBV/Pa vs frequency, “Static Diaphragm Displacement” which will plot the shape of the diaphragm in its initial condition that results from the electrical force on it, and “Polar Response” which will show the microphone’s output at a varying incidence angle relative to its on-axis output.

In addition, the screen displays the active capacitance in the bottom lefthand corner. The frequency response display will show all incidence angles with their own-colored lines, outlined in the legend on the plot.

The static diaphragm displacement is an extremely helpful metric when trying to maximize the sensitivity of a condenser cartridge and is helpful to understand the risk of a diaphragm collapse. The displacement of the diaphragm through the x-axis and the y-axis are both plotted with a red-dotted line indicating the theoretical collapse limit of 1/3 the height of the air gap [4], as shown in Figure 7.

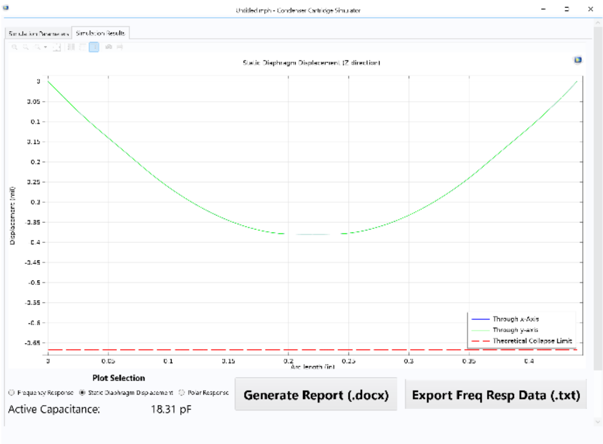


Figure 5: Simulation Results Screen in the Application set to view the Static Diaphragm Displacement

The polar response plot is one of the best ways to visually display the directionality of a microphone cartridge. A full polar plot is displayed if the frequency resolution settings on the parameters page is set to “Polar Plot.” There is an assumption of symmetry about the main axis, so the response is only simulated from 0˚ to 180˚ and mirrored in the plot. The program also allows for results to be output in a report generated by COMSOL. The “Generate Report (.docx)” button will create a multi-page report that includes all the parameters simulated and the results in both plots and tables. The frequency response data can also be saved to a .txt file using the “Export Freq Resp Data (.txt)” button if the entire report is not desired.

Model Validation

To ensure the setup of the model would produce results that would be most useful to a design engineer, a sample cartridge was built and tested and had frequency response curves compared to a simulation of that design.

Figure 6: Image of Half Inch Cardioid Cartridge Built and Tested to Validate Model

The cartridge pictured in Figure 8 was built that is ½” inch in diameter with a large front opening and a backplate with five holes. The phase shift network made of a cylindrical plastic piece to create an air cavity and a wire mesh selectively covered in adhesive to create an acoustic resistance of 1150 cgs ohms to tune to a cardioid polar pattern. An equivalent circuit analysis and further details of the parts used to build this cartridge is outlined in a separate paper [5].

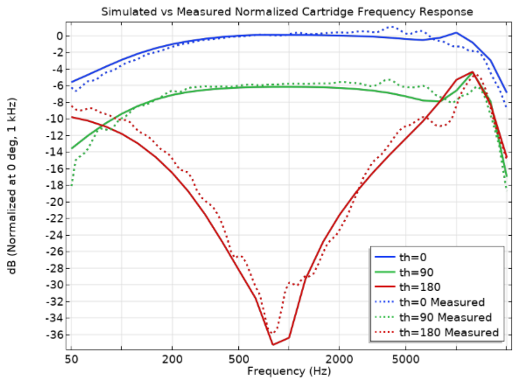


Figure 7: Cartridge Frequency Response Normalized at 1 kHz Measured (Dashed) vs Simulated (Solid) at 2 ft Source Distance and Incidence Angles of 0º (Blue), 90º (Green), and 180º (Red).

The prototype cartridge shown here was measured in a full anechoic chamber at Shure's headquarters in Niles, IL. The measurement was taken at a 2 ft source distance with fixturing designed to minimize impacts on the measurement. While there are simplifications of the geometry in the model, like the omission of the contact pin allowing for connection to the backplate, the simulated response was quite close to measured response, differing only at most 1 dB across the frequency range. The geometry of the phase shift network was simplified in the simulation but still produced a result with good correlation. The simulation techniques used here have also been implemented directly to geometry of another cartridge design from CAD software and showed similar correlation results.

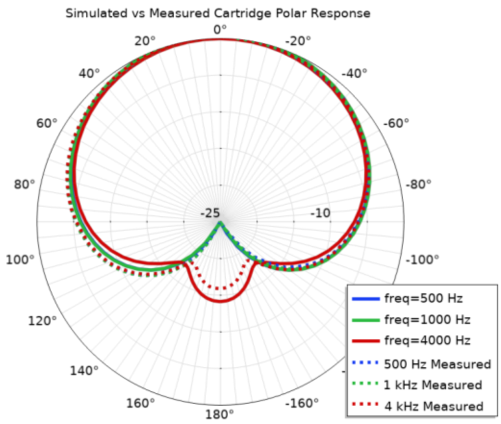


Figure 8: Cartridge Polar Response Measured (Dashed) vs Simulated (Solid) at 2 ft Source Distance at frequency of 500 Hz (Green), 1 kHz (Blue) and 4 kHz

Conclusions

When attempting to model the acoustical response of a directional condenser microphone, COMSOL can be an incredibly useful tool. The ability to parameterize the entire geometry in the model is powerful, allowing for a simulated cartridge to be altered quickly without having to re-assign physics and meshing. With this setup, parameters from mechanical drawings and spec sheets can be enough to simulate the acoustic response without having to create lumped element approximations of acoustic components. Even a novice COMSOL user or engineer who is new to microphone design can use this tool to reduce design iteration time and understand the contribution of specific aspects of the design. While the geometry template identified in this application is a bit limiting, the structure of this model can be applied to any complex geometry. Future areas of work may include investigation of modeling the phase shift network for small cartridges with internal thermo-viscous losses like this model accounts for in the air gap and more options for geometry editing to allow for more cartridge topologies to be simulated easily.

References

[1] COMSOL, "The Brüel & Kjær 4134 Condenser Microphone," https://www.comsol.com/model/the-br-252-el-kj-230-r-4134-condenser-microphone-12375

[2] COMSOL, "Acoustics Module User's Guide" https://doc.comsol.com/5.3/doc/com.comsol.help.aco/AcousticsModuleUsersGuide.pdf, pp 384

[3] COMSOL, "Acoustics Module User's Guide" https://doc.comsol.com/5.3/doc/com.comsol.help.aco/AcousticsModuleUsersGuide.pdf, pp 54

[4] Hunt, F.V. "Electroacoustics: The Analysis of Transduction and its Historical Background," *American Institute of Physics*, pp. 183, 1982.

[5] Cillo, J. "Example Design of a Half-Inch Diameter Uni-Directional Electret Condenser Cartridge" M.Eng Acoustics Paper, *The Pennsylvania State University*, 2022

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