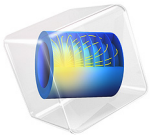


Model created in COMSOL Multiphysics 6.4

Full Ear Hearing Aid Response

Introduction

This model demonstrates how to perform a hearing aid acoustic feedback response analysis, including both the in-ear hearing aid and the hearing aid cassette. The model is of a ReSound OMNIA™ RIE (receiver-in-the-ear) hearing aid device from GN Hearing A/S.[1] The hearing aid is tested on the combined pinna and ear canal that is defined in the ITU-T P.57 standard, Ref. 1 and Ref. 2. This is the P.57 Type 4.3 full-band ear simulator that is presented in the Application Library model Type 4.3 Ear Simulator, hence the model is created entirely on information available in the ITU-T P.57 standard. It is not a model of a particular, commercially available, ear simulator.

The model calculates the sound pressure level at the eardrum and compares with measurements, Ref. 3.[2] The model also simulates the acoustic field outside the ear and includes the acoustic feedback to the two microphones located on the hearing aid cassette, see Figure 1. The acoustic response at the eardrum is characterized by the geometrical features of the ear and earbud and by the viscous losses in the earbud, especially the narrow regions in the wax guard and the vent holes.

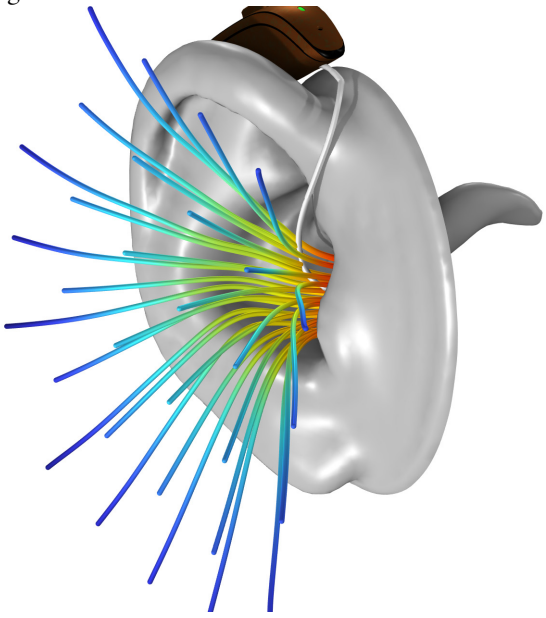


Figure 1: Illustrative figure of the model geometry with the ear simulator, hearing aid, and streamlines of the intensity of the acoustic field leaking from the ear canal.

[1] The hearing aid geometry is copyright and courtesy of GN Hearing A/S. [2] Measurements are courtesy of Hottinger Brüel og Kjaer A/S.

Model Definition

The model geometry consists of the ear, the earbud, and the hearing aid cassette. Only the air domain is considered and pressure acoustics is used to model the acoustic field. The acoustic field is actuated by a speaker in the earbud. A lumped representation is used to model the speaker in the earbud which is implemented using the **Lumped Port** boundary condition. To model the correct damping in the system both the **Narrow Region Acoustics** and the **Thermoviscous Boundary Layer Impedance** features are used where appropriate. It is important to model the losses accurately since the damping is important to achieve the correct sound pressure levels and response. Outside the ear, the **Perfectly Matched Boundary** is used to mimic an infinite baffle around the outer ear and hearing aid cassette.

The geometry is made from three different geometry files that are combined. The hearing aid cassette and earbud are imported as geometry parts, see Figure 2. They are prepared by removing details and features that are unimportant for the model and would be expensive to resolve numerically. This is achieved using **Virtual Operations** in the Geometry such as **Collapse Faces**, **Merge Edges**, and **Ignore Vertices**. The geometry is shown in Figure 3. The air domains in the ear canal and outside the hearing aid are connected by two narrow vent holes. The two vent holes are the only sources for acoustic energy to propagate outside the ear canal since the structural vibrations of the hearing aid are neglected.

To accurately model the acoustic response, we are using a lumped model of the hearing aid speaker (the so-called hearing aid receiver) and a specific impedance for the eardrum, Ref. 2. To transform the pressure at the microphones to an electrical signal, we are using a set of sensitivity parameters for the microphones. The transfer matrix or ABCS-parameters for the speaker and microphone sensitivity curves are courtesy of GN Hearing A/S. The data for the speaker and microphone is defined up to 10 kHz, at higher frequencies the values at 10 kHz are used.

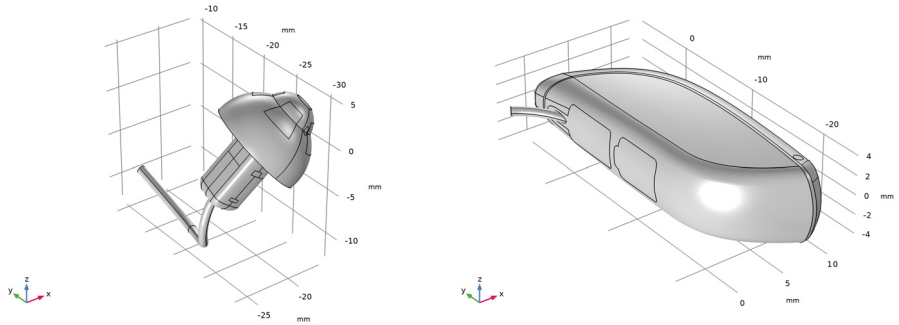


Figure 2: Geometry of the earbud (left) and hearing aid cassette (right). Hearing aid geometry copyright and courtesy of GN Hearing A/S.

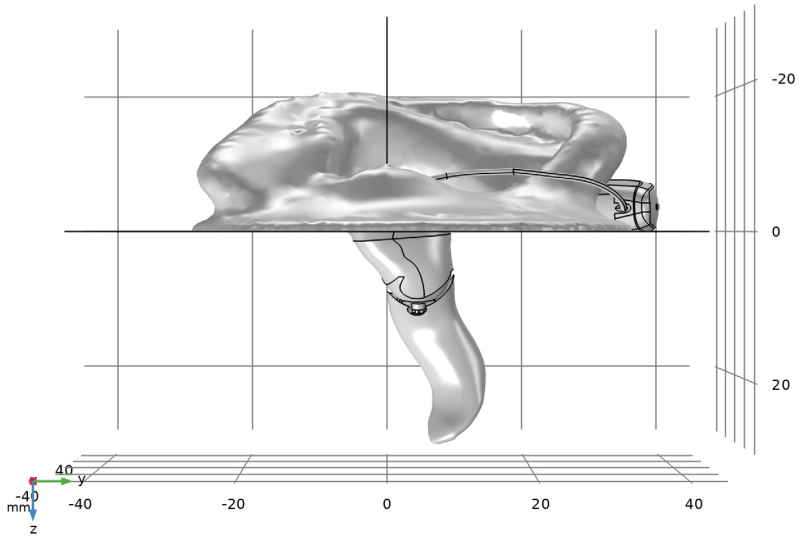


Figure 3: Geometry of the full model including the ear and hearing aid. Hearing aid geometry copyright and courtesy of GN Hearing A/S.

Results and Discussion

The main result is the acoustic pressure and sound pressure level inside and outside the ear. The acoustic response at the eardrum is compared to measurements in the range from 20 Hz to 20 kHz in Figure 4. An average measurement result is calculated from five individual measurements, where the earbud has been positioned in the ear canal (of a commercial available Type 4.3 Ear Simulator), measured and then remove from the ear canal again. Each measurement is represented by a dashed black line, the average by a thick red line, and the dashed red lines are the six standard deviation uncertainty limits.

In general, the model matches the acoustic response well. The roll-off toward lower frequencies is caused by the acoustic leakage of the two vents in the dome. At higher frequencies, resonances appear. The model catches the resonances but the peaks are shifted slightly toward higher frequencies. The placement of the resonances are determined by the geometry of the ear canal and how far into the ear the earbud is placed. The resonance peaks at 8 kHz and 14 kHz correspond to a half wave and full wave resonances in the ear canal. The acoustic pressure at the two resonance peaks is shown in Figure 5.

The simulated response does have a resonance peak around 700 Hz which does not exist or is heavily suppressed in the measurement data. This peak is the Helmholtz resonance of the air volume in the ear canal.

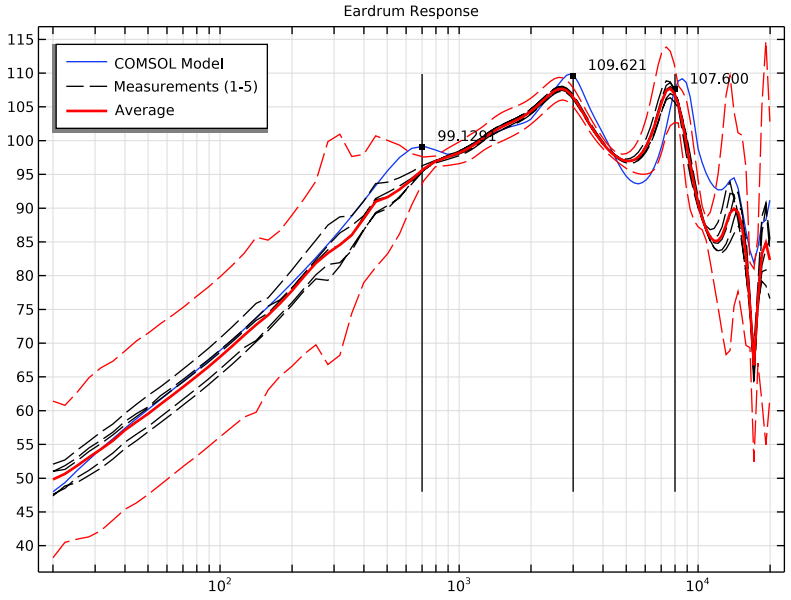


Figure 4: Acoustic response at the eardrum from the model and from measurements. Measurements courtesy of Hottinger Brüel and Kjær A/S. The black dashed lines are the five individual measurements using a commercially available Type 4.3 Ear Simulator. The thick red line is the experimental average while the dashed red lines represent six standard deviations. The blue line is the modeled acoustic response.

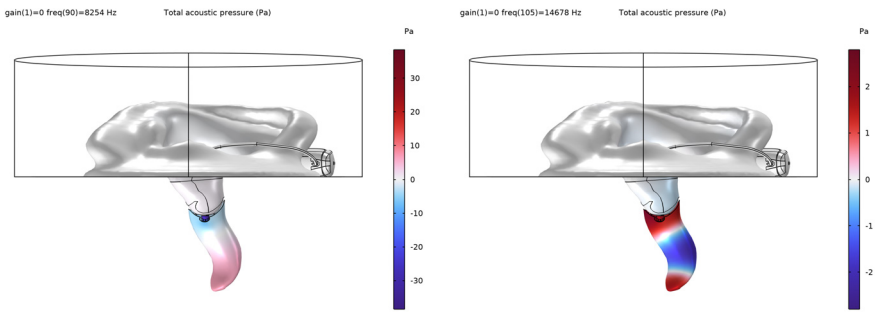


Figure 5: Acoustic pressure in the ear one half and one wavelength resonances at 8000 Hz (left) and 14000 Hz (right).

The acoustic field outside the ear is very weak compared to inside the ear. The sound does leak out and results in feedback in the microphones in the hearing aid cassette. The sound pressure level outside the ear is shown in Figure 6 at 20 Hz, 200 Hz, 2 kHz, and 20 kHz.

The feedback at the two microphones at the hearing aid cassette is shown in Figure 7, with both the absolute value and phase of the acoustic feedback in the microphones. Positive feedback occurs when the feedback is in phase with the actuation, thus when the phase is zero. The phase of the two microphones are slightly shifted since the two microphones are positioned at different distance relative to the ear canal. The feedback is in phase around 1100 Hz, 3300 Hz, 7500 Hz, and 9100 Hz and it is expected to see positive feedback at these frequencies at high gain of the hearing aid.

In Figure 8, the gain has been set to 0 and 500, a gain of 0 corresponds to no acoustic feedback and a gain of 500 here means that the actuation voltage is 500 times larger than the voltage measured at the microphones. In this model, a simple constant gain has been used. It is possible to make the gain frequency dependent. With a gain of 500, the acoustic feedback causes resonances at the frequencies where the acoustic feedback is in phase with the actuation.

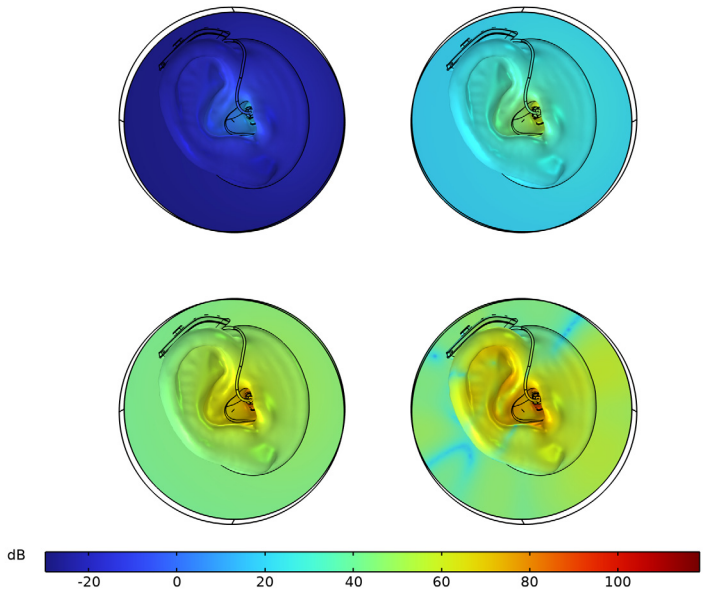


Figure 6: Sound pressure level outside the ear at 20 Hz (top left), 200 Hz (top right), 2000 Hz (bottom left), and 20 kHz (bottom right).

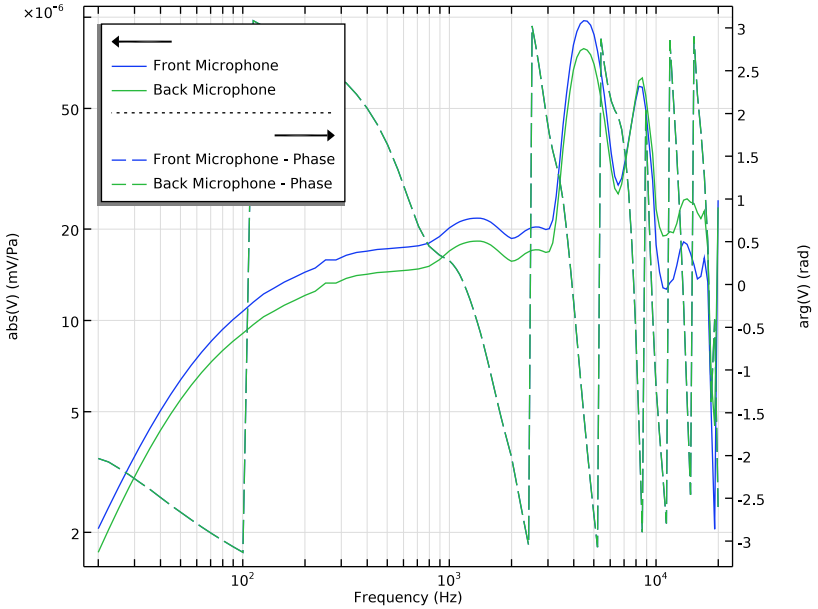


Figure 7: Acoustic feedback at the two microphones on the hearing aid cassette. With solid lines, the absolute value of the feedback in mV/Pa and in dashed lines, the phase in radians.

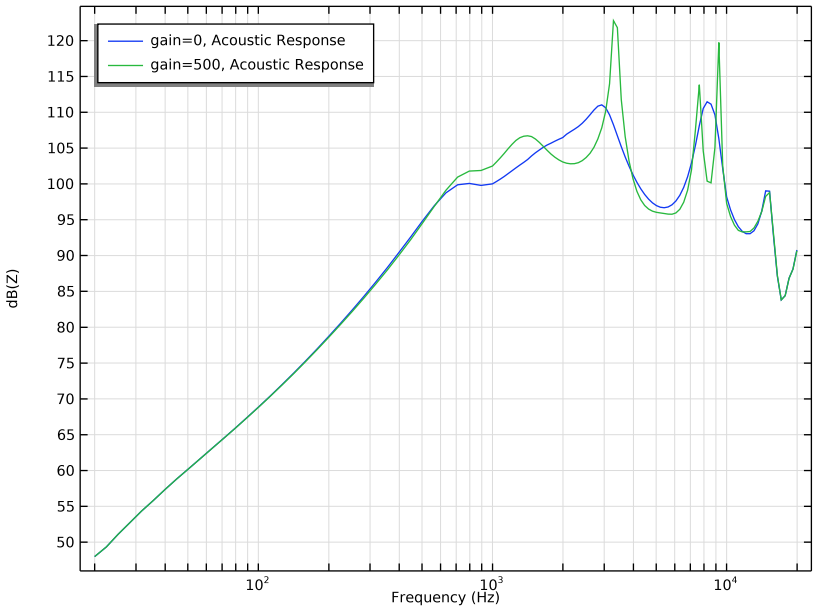


Figure 8: The acoustic response at the eardrum with no feedback and a gain of 500. Resonance peaks develop at the frequencies where the feedback is in phase with the actuation.

Notes About the COMSOL Implementation

The geometry has been cleaned up to make the simulation easier. For the clean up, a variety of virtual geometry operations have been used including **Form Composite Faces**, **Collapse Faces**, **Merge Vertices**, and **Ignore Vertices**. This is done to remove fine details which do not influence the acoustics but do need a very fine mesh to resolve.

Note also that the model uses linear elements for the pressure field degree of freedom. This is done because there are a lot of narrow domains where the restriction on the mesh is defined by the geometry and not the wavelength. For linear elements it is recommended to use at least 12 elements per wavelength. The latter only really applies outside the ear in the current model.

References

1. ITU-T Recommendation P.57: Artificial Ears. 2021.

2. L.B. Nielsen and M. Herring Jensen, “The Digital Twin of a New and Standardized Fullband Ear Simulator,” DAGA 2022.

3. L.B. Nielsen and M. Herring Jensen, “Simulation and Physical Testing using Standardized Ear Simulators,” DAGA 2023.

Application Library path: `Acoustics_Module/Electroacoustic_Transducers/full_ear_hearing_aid`

Modeling Instructions

From the **File** menu, choose **New**.

NEW

In the **New** window, click **Model Wizard**.

MODEL WIZARD

1 In the **Model Wizard** window, click **3D**.

2 In the **Select Physics** tree, select **Acoustics** > **Pressure Acoustics** > **Pressure Acoustics, Frequency Domain (acpr)**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **General Studies** > **Frequency Domain**.

6 Click **Done**.

GLOBAL DEFINITIONS

Parameters 1

The model parameters are loaded from the file `full_ear_hearing_aid_parameters.txt`.

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

2 In the **Settings** window for **Parameters**, locate the **Parameters** section.

3 Click **Load from File**.

4 Browse to the model’s Application Libraries folder and double-click the file `full_ear_hearing_aid_parameters.txt`.

GEOMETRY 1

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometry 1**.

2 In the **Settings** window for **Geometry**, locate the **Units** section.

3 From the **Length unit** list, choose **mm**.

4 Locate the **Advanced** section. From the **Geometry representation** list, choose **CAD kernel**.

5 Select the **Design Module Boolean operations** checkbox.

6 In the **Geometry** toolbar, click **Insert Sequence** and choose **Insert Sequence**.

7 Browse to the model's Application Libraries folder and double-click the file `full_ear_hearing_aid_geom_sequence.mph`.

8 In the **Insert Sequence** dialog, click **OK**.

9 In the **Geometry** toolbar, click **Build All**.

DEFINITIONS

View 1

Hide boundaries to make it easier to visualize the model.

Hide for Geometry 1

1 In the **Model Builder** window, expand the **Component 1 (comp1)** > **Definitions** node.

2 Right-click **View 1** and choose **Hide for Geometry**.

3 In the **Settings** window for **Hide for Geometry**, locate the **Selection** section.

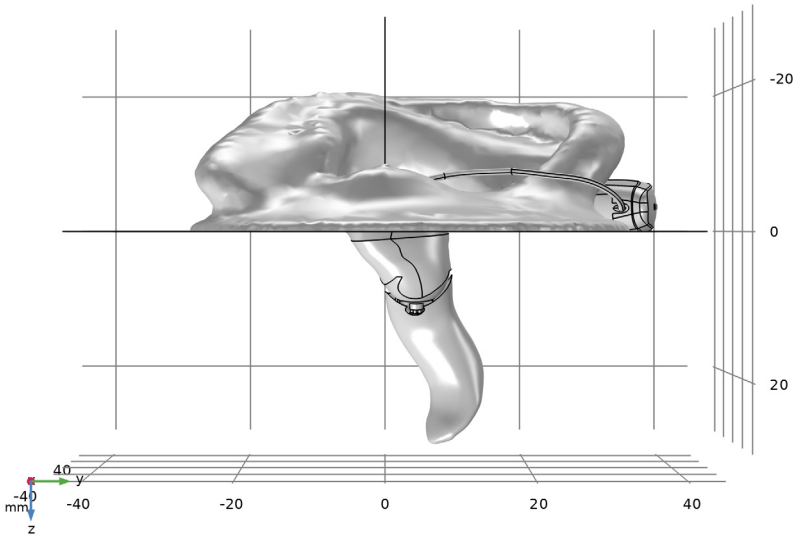
4 From the **Geometric entity level** list, choose **Boundary**.

5 On the object **cle1**, select Boundaries 1–3, 141, and 142 only.

GEOMETRY 1

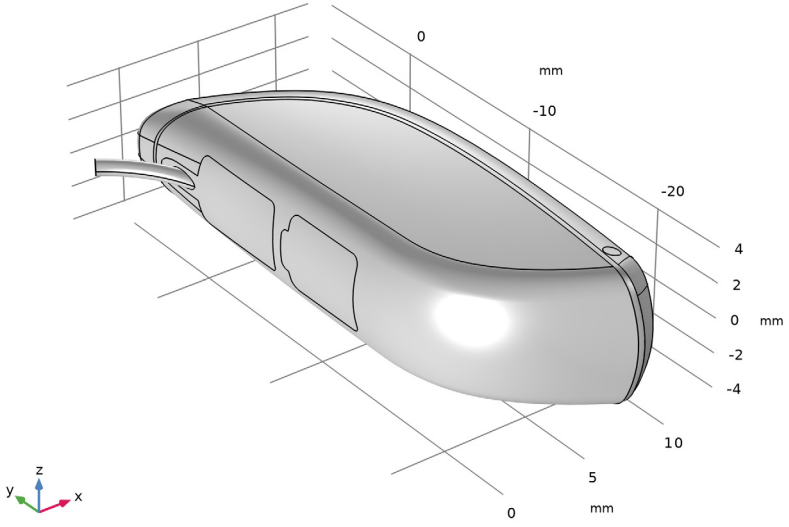
1 In the **Geometry** toolbar, click **Build All**.

2 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometry 1**.



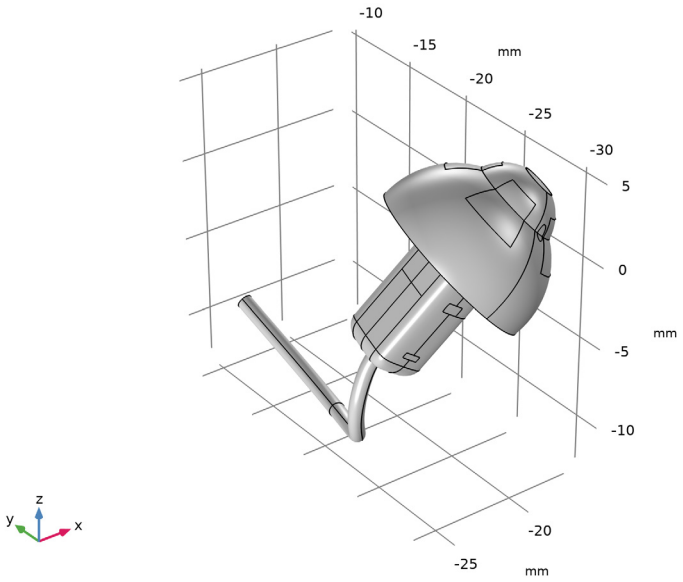
PART I

In the **Model Builder** window, expand the **Global Definitions** > **Geometry Parts** node, then click **Part 1**.



EAR BUD

In the **Model Builder** window, under **Global Definitions** > **Geometry Parts** click **Ear bud**.



Load in data files for the ear drum impedance, the hearing aid lumped speaker parameters, microphone sensitivity, and experimental data.

GLOBAL DEFINITIONS

Interpolation 1 (int1)

1 In the **Home** toolbar, click f(x) **Functions** and choose **Global** > **Interpolation**.

2 In the **Settings** window for **Interpolation**, locate the **Definition** section.

3 From the **Data source** list, choose **File**.

4 In the **Filename** text field, type `full_ear_hearing_aid_impedance.txt`.

5 Locate the **Data Column Settings** section. In the table, click to select the cell at row number 1 and column number 1.

6 In the **Unit** text field, type 1.

7 In the table, enter the following settings:

Columns	Type	Settings
absZ (kg/(m^2*s))	Function values	Function name=absZ

8 In the **Name** text field, type `absZ`.

9 In the **Unit** text field, type `kg/(m^2*s)`.

10 In the table, click to select the cell at row number 3 and column number 1.

11 In the **Name** text field, type `argZ`.

12 In the **Unit** text field, type `rad`.

13 Locate the **Definition** section. Click **Import**.

14 Click **Plot**.

Interpolation 2 (int2)

1 In the **Home** toolbar, click **Functions** and choose **Global** > **Interpolation**.

2 In the **Settings** window for **Interpolation**, locate the **Definition** section.

3 From the **Data source** list, choose **File**.

4 In the **Filename** text field, type `full_ear_hearing_aid_abcd.dat`.

5 Locate the **Data Column Settings** section. In the table, enter the following settings:

Columns	Type	Settings
Column 2	Function values	Function name=int2a
Column 3	Function values	Function name=int2b
Column 5	Function values	Function name=int2c
Column 6	Function values	Function name=int2d
Column 7	Function values	Function name=int2e
Column 8	Function values	Function name=int2f
Column 9	Function values	Function name=int2g

6 In the table, click to select the cell at row number 1 and column number 1.

7 In the **Unit** text field, type `Hz`.

8 In the table, click to select the cell at row number 2 and column number 1.

9 In the **Name** text field, type `Ar`.

10 In the table, click to select the cell at row number 3 and column number 1.

11 In the **Name** text field, type `Ai`.

12 In the table, click to select the cell at row number 4 and column number 1.

13 In the **Name** text field, type `Br`.

14 In the table, click to select the cell at row number 5 and column number 1.

15 In the **Name** text field, type `Bi`.

16 In the table, click to select the cell at row number 6 and column number 1.

17 In the **Name** text field, type `Cr`.

18 In the table, click to select the cell at row number 7 and column number 1.

19 In the **Name** text field, type `Ci`.

20 In the table, click to select the cell at row number 8 and column number 1.

21 In the **Name** text field, type `Dr`.

22 In the table, click to select the cell at row number 9 and column number 1.

23 In the **Name** text field, type `Di`.

24 Locate the **Definition** section. Click **Import**.

25 Click **Plot**.

Interpolation 3 (int3)

1 In the **Home** toolbar, click **Functions** and choose **Global** > **Interpolation**.

2 In the **Settings** window for **Interpolation**, locate the **Definition** section.

3 From the **Data source** list, choose **File**.

4 In the **Filename** text field, type `full_ear_hearing_aid_measurements.txt`.

5 Locate the **Data Column Settings** section. In the table, enter the following settings:

Columns	Type	Settings
Column 2	Function values	Function name=int3a
Column 3	Function values	Function name=int3b
Column 5	Function values	Function name=int3c
Column 6	Function values	Function name=int3d
Column 7	Function values	Function name=int3e
Column 8	Function values	Function name=int3f
Column 9	Function values	Function name=int3g

6 In the table, click to select the cell at row number 1 and column number 1.

7 In the **Unit** text field, type `Hz`.

8 In the table, click to select the cell at row number 2 and column number 1.

9 In the **Name** text field, type `L1`.

10 In the **Unit** text field, type `dB`.

11 In the table, click to select the cell at row number 3 and column number 1.

12 In the **Name** text field, type `L2`.

13 In the **Unit** text field, type `dB`.

14 In the table, click to select the cell at row number 4 and column number 1.

15 In the **Name** text field, type `L3`.

16 In the **Unit** text field, type `dB`.

17 In the table, click to select the cell at row number 5 and column number 1.

18 In the **Name** text field, type `L4`.

19 In the **Unit** text field, type `dB`.

20 In the table, click to select the cell at row number 6 and column number 1.

21 In the **Name** text field, type `L5`.

22 In the **Unit** text field, type `dB`.

23 In the table, click to select the cell at row number 7 and column number 1.

24 In the **Name** text field, type `Lav`.

25 In the **Unit** text field, type `dB`.

26 In the table, click to select the cell at row number 8 and column number 1.

27 In the **Name** text field, type `Lpsigma`.

28 In the **Unit** text field, type `dB`.

29 In the table, click to select the cell at row number 9 and column number 1.

30 In the **Name** text field, type `Lmsigma`.

31 In the **Unit** text field, type `dB`.

32 Locate the **Definition** section. Click **Import**.

33 Click **Plot**.

Interpolation 4 (int4)

1 In the **Home** toolbar, click **Functions** and choose **Global** > **Interpolation**.

2 In the **Settings** window for **Interpolation**, locate the **Definition** section.

3 From the **Data source** list, choose **File**.

4 In the **Filename** text field, type `full_ear_hearing_aid_microphonesensitivity.txt`.

5 Locate the **Data Column Settings** section. In the table, click to select the cell at row number 1 and column number 1.

6 In the **Unit** text field, type `Hz`.

7 In the table, enter the following settings:

Columns	Type	Settings
Column 2	Function values	Function name=int4a
Column 3	Function values	Function name=int4b
Column 4	Ignored column	

8 In the table, click to select the cell at row number 2 and column number 1.

9 In the **Name** text field, type `Tr`.

10 In the **Unit** text field, type `V/Pa`.

11 In the table, click to select the cell at row number 3 and column number 1.

12 In the **Name** text field, type `Ti`.

13 In the **Unit** text field, type `V/Pa`.

14 Locate the **Definition** section. Click **Import**.

15 Click **Plot**.

GEOMETRY 1

Cleanup Log

1 In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Average**.

2 In the **Geometry Cleanup** dialog that opens, click **Clean up Automatically** to automatically clean up the geometry.

DEFINITIONS

Average 1 (aveop1)

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Definitions** click **Average 1 (aveop1)**.

2 In the **Settings** window for **Average**, type `aveop_ed` in the **Operator name** text field.

3 Locate the **Source Selection** section. From the **Geometric entity level** list, choose **Boundary**.

4 From the **Selection** list, choose **Ear Drum**.

Average 2 (aveop2)

1 In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Average**.

2 In the **Settings** window for **Average**, type `aveop_mic` in the **Operator name** text field.

3 Locate the **Source Selection** section. From the **Geometric entity level** list, choose **Boundary**.

4 From the **Selection** list, choose **Microphones**.

ADD MATERIAL

1 In the **Home** toolbar, click **Add Material** to open the **Add Material** window.

2 Go to the **Add Material** window.

3 In the tree, select **Built-in** > **Air**.

4 Click the **Add to Component** button in the window toolbar.

5 In the **Home** toolbar, click **Add Material** to close the **Add Material** window.

PRESSURE ACOUSTICS, FREQUENCY DOMAIN (ACPR)

1 In the **Settings** window for **Pressure Acoustics, Frequency Domain**, click to expand the **Discretization** section.

2 From the **Element order** list, choose **Linear**.

Lumped Port 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Lumped Port**.

2 In the **Settings** window for **Lumped Port**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Speaker**.

4 Locate the **Connection Type** section. From the **Two-port representation** list, choose **Electroacoustic**.

5 In the T_{11} text field, type `Ar(freq)+i*Ai(freq)`.

6 In the T_{12} text field, type `Br(freq)+i*Bi(freq)`.

7 In the T_{21} text field, type `Cr(freq)+i*Ci(freq)`.

8 In the T_{22} text field, type `Dr(freq)+i*Di(freq)`.

9 Locate the **Source Settings** section. In the V_{in} text field, type `V0+(Tr(freq)+i*Ti(freq))*aveop_mic(acpr.p_t)*gain`.

Impedance - Ear Drum

1 In the **Physics** toolbar, click **Boundaries** and choose **Impedance**.

2 In the **Settings** window for **Impedance**, type `Impedance - Ear Drum` in the **Label** text field.

3 Locate the **Boundary Selection** section. From the **Selection** list, choose **Ear Drum**.

4 Locate the **Impedance** section. In the Z_n text field, type `absZ(log10(freq[1/Hz]))*exp(i*argZ(log10(freq[1/Hz])))`.

Thermoviscous Boundary Layer Impedance 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Thermoviscous Boundary Layer Impedance**.

2 In the **Settings** window for **Thermoviscous Boundary Layer Impedance**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Ear Canal - TVBLI Boundaries**.

4 Locate the **Fluid Properties** section. From the **Fluid material** list, choose **Air (mat1)**.

Include the losses in the thin domains by the Narrow Region Acoustics feature.

Narrow Region Acoustics - Vent Holes

1 In the **Physics** toolbar, click **Domains** and choose **Narrow Region Acoustics**.

2 In the **Settings** window for **Narrow Region Acoustics**, type `Narrow Region Acoustics - Vent Holes` in the **Label** text field.

3 Locate the **Domain Selection** section. From the **Selection** list, choose **Vent Holes**.

4 Locate the **Duct Properties** section. From the **Duct type** list, choose **Circular duct**.

5 In the a text field, type `a_vent`.

Narrow Region Acoustics - Wax Guard Holes

1 In the **Physics** toolbar, click **Domains** and choose **Narrow Region Acoustics**.

2 In the **Settings** window for **Narrow Region Acoustics**, type `Narrow Region Acoustics - Wax Guard Holes` in the **Label** text field.

3 Locate the **Domain Selection** section. From the **Selection** list, choose **Wax Guard Holes**.

4 Locate the **Duct Properties** section. From the **Duct type** list, choose **Circular duct**.

5 In the a text field, type `0.5*0.4[mm]`.

Wax Guard

1 In the **Physics** toolbar, click **Domains** and choose **Narrow Region Acoustics**.

2 In the **Settings** window for **Narrow Region Acoustics**, locate the **Domain Selection** section.

3 From the **Selection** list, choose **Ear-Bud Domain**.

4 In the **Label** text field, type `Wax Guard`.

5 Locate the **Duct Properties** section. From the **Duct type** list, choose **Circular duct**.

6 In the a text field, type `a_port`.

Perfectly Matched Boundary is used to mimic an infinite baffle.

Perfectly Matched Boundary 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Perfectly Matched Boundary**.

2 Select Boundaries 1–3, 141, and 142 only.

MESH 1

Free Tetrahedral 1

In the **Mesh** toolbar, click  **Free Tetrahedral**.

Size 1

1 Right-click **Free Tetrahedral 1** and choose **Size**.

Set a finer mesh size in the thin regions.

2 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.

3 From the **Geometric entity level** list, choose **Domain**.

4 Select Domains 4, 5, and 7–13 only.

5 Locate the **Element Size** section. Click the **Custom** button.

6 Locate the **Element Size Parameters** section.

7 Select the **Maximum element size** checkbox. In the associated text field, type `a_vent/3`.

Size 2

1 In the **Model Builder** window, right-click **Free Tetrahedral 1** and choose **Size**.

2 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.

3 From the **Geometric entity level** list, choose **Domain**.

4 Select Domain 2 only.

5 Locate the **Element Size** section. Click the **Custom** button.

6 Locate the **Element Size Parameters** section.

7 Select the **Minimum element size** checkbox. In the associated text field, type `a_vent/3`.

8 Select the **Maximum element growth rate** checkbox. In the associated text field, type `1.3`.

Size

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Mesh 1** click **Size**.

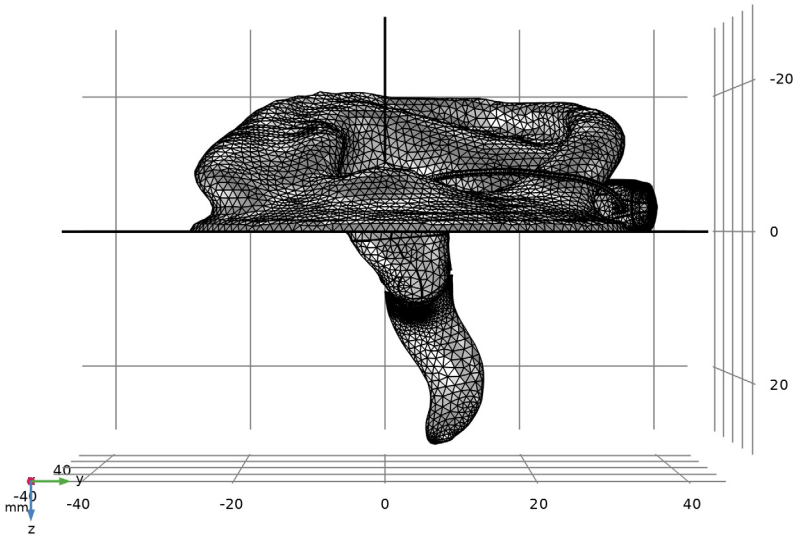
2 In the **Settings** window for **Size**, click to expand the **Element Size Parameters** section.

3 Locate the **Element Size** section. Click the **Custom** button.

4 Locate the **Element Size Parameters** section. In the **Maximum element size** text field, type `h_max`.

5 In the **Minimum element size** text field, type `h_max/2`.

6 Click **Build All**.



STUDY 1

Step 1: Frequency Domain

A finer step size is chosen for the higher frequencies. This is to resolve the resonance peaks appearing when the gain is nonzero.

1 In the **Model Builder** window, under **Study 1** click **Step 1: Frequency Domain**.

2 In the **Settings** window for **Frequency Domain**, locate the **Study Settings** section.

3 In the **Frequencies** text field, type `{10^{range(log10(20),1/20,log10(950))} 10^{range(log10(1000),1/60,log10(20000))}}`.

4 Click to expand the **Results While Solving** section. From the **Probes** list, choose **None**.

Show the default solver suggestions and enable an iterative solver suggestion.

Solution 1 (sol1)

1 In the **Study** toolbar, click **Show Default Solver**.

2 In the **Model Builder** window, expand the **Solution 1 (sol1)** node.

3 In the **Model Builder** window, expand the **Study 1** > **Solver Configurations** > **Solution 1 (sol1)** > **Stationary Solver 1** node.

4 Right-click **Study 1** > **Solver Configurations** > **Solution 1 (sol1)** > **Stationary Solver 1** > **Suggested Iterative Solver (GMRES with GMG) (acpr)** and choose **Enable**.

Parametric Sweep

1 In the **Study** toolbar, click **Parametric Sweep**.

2 In the **Settings** window for **Parametric Sweep**, locate the **Study Settings** section.

3 Click **Add**.

4 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
gain (Gain of hearing aid)	`0, 500`	

5 In the **Study** toolbar, click **Compute**.

Create a plot for the acoustic response on the ear drum including both the experimental measurements and the simulation results.

RESULTS

Eardrum Response

1 In the **Results** toolbar, click **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 1/Parametric Solutions 1 (sol2)**.

4 From the **Parameter selection (gain)** list, choose **First**.

5 Locate the **Legend** section. From the **Position** list, choose **Upper left**.

6 In the **Label** text field, type `Eardrum Response`.

7 Click to expand the **Title** section. From the **Title type** list, choose **Label**.

Octave Band 1

1 In the **Eardrum Response** toolbar, click **More Plots** and choose **Octave Band**.

2 In the **Settings** window for **Octave Band**, locate the **Selection** section.

3 From the **Geometric entity level** list, choose **Boundary**.

4 From the **Selection** list, choose **Ear Drum**.

5 Locate the **y-Axis Data** section. In the **Amplitude reference** text field, type `acpr.pref_SPL*sqrt(2)`.

6 Locate the **Plot** section. From the **Quantity** list, choose **Continuous power spectral density**.

7 Click to expand the **Legends** section. Select the **Show legends** checkbox.

8 From the **Legends** list, choose **Manual**.

9 In the table, enter the following settings:

Legends
COMSOL Model

Graph Marker 1

1 Right-click **Octave Band 1** and choose **Graph Marker**.

2 In the **Settings** window for **Graph Marker**, locate the **Display** section.

3 From the **Display mode** list, choose **Line intersection**.

4 In the **x-coordinates** text field, type `700 3000 8000`.

5 Select the **Show lines** checkbox.

Measurements (1)

1 In the **Model Builder** window, right-click **Eardrum Response** and choose **Global**.

2 In the **Settings** window for **Global**, type `Measurements (1)` in the **Label** text field.

3 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
L1(freq)	dB	Interpolation 3

4 Click to expand the **Legends** section. From the **Legends** list, choose **Manual**.

5 In the table, enter the following settings:

Legends
Measurements (1-5)

6 Click to expand the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Dashed**.

7 From the **Color** list, choose **Black**.

Measurements (2-5)

1 Right-click **Measurements (1)** and choose **Duplicate**.

2 In the **Settings** window for **Global**, type `Measurements (2-5)` in the **Label** text field.

3 Locate the **Legends** section. Clear the **Show legends** checkbox.

4 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
`L2(freq)`	`dB`	`Interpolation 3`
`L3(freq)`	`dB`	`Interpolation 3`
`L4(freq)`	`dB`	`Interpolation 3`
`L5(freq)`	`dB`	`Interpolation 3`

5 In the **Eardrum Response** toolbar, click **Plot**.

Measurements (Average)

1 In the **Model Builder** window, right-click **Measurements (1)** and choose **Duplicate**.

2 In the **Settings** window for **Global**, type `Measurements (Average)` in the **Label** text field.

3 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
`Lav(freq)`	`dB`	`Interpolation 3`

4 Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Solid**.

5 From the **Color** list, choose **Red**.

6 From the **Width** list, choose **2**.

7 Locate the **Legends** section. In the table, enter the following settings:

Legends
`Average`

8 In the **Eardrum Response** toolbar, click **Plot**.

Measurements (+-sigma)

1 Right-click **Measurements (Average)** and choose **Duplicate**.

2 In the **Settings** window for **Global**, type `Measurements (+-sigma)` in the **Label** text field.

3 Locate the **y-Axis Data** section. In the table, enter the following settings:

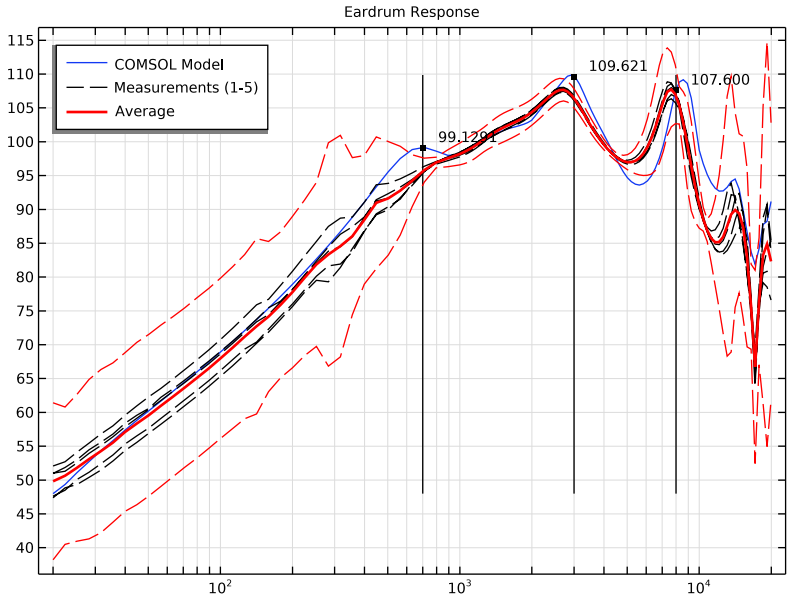
Expression	Unit	Description
`Lmsigma(freq)`	`dB`	`Interpolation 3`
`Lpsigma(freq)`	`dB`	`Interpolation 3`

4 Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Dashed**.

5 From the **Width** list, choose **Default from preferences (1)**.

6 Locate the **Legends** section. Clear the **Show legends** checkbox.

7 In the **Eardrum Response** toolbar, click **Plot**.



Create a plot for the acoustic feedback at the microphones. Plot both the amplitude and phase of the acoustic feedback.

Microphones

1 In the **Results** toolbar, click **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `Microphones` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 1/ Parametric Solutions 1 (sol2)**.

4 From the **Parameter selection (gain)** list, choose **First**.

5 Locate the **Legend** section. From the **Position** list, choose **Upper left**.

Front Microphone

1 In the **Microphones** toolbar, click **More Plots** and choose **Octave Band**.

2 In the **Settings** window for **Octave Band**, type `Front Microphone` in the **Label** text field.

3 Locate the **Selection** section. From the **Geometric entity level** list, choose **Boundary**.

4 From the **Selection** list, choose **Front Microphone**.

5 Locate the **y-Axis Data** section. In the **Expression** text field, type `abs((Tr(freq)+i*Ti(freq))*acpr.p_t)`.

6 From the **Expression type** list, choose **General (non-dB)**.

7 In the **Reference expression** text field, type `aveop_ed(abs(acpr.p_t))`.

8 Locate the **Plot** section. From the **Quantity** list, choose **Continuous power spectral density**.

9 Locate the **Legends** section. Select the **Show legends** checkbox.

10 From the **Legends** list, choose **Manual**.

11 In the table, enter the following settings:

Legends
Front Microphone

Back Microphone

1 Right-click **Front Microphone** and choose **Duplicate**.

2 In the **Settings** window for **Octave Band**, type `Back Microphone` in the **Label** text field.

3 Locate the **Selection** section. Click to select the  **Activate Selection** toggle button.

4 From the **Selection** list, choose **Back Microphone**.

5 Locate the **Legends** section. In the table, enter the following settings:

Legends
Back Microphone

6 Click the  **y-Axis Log Scale** button in the **Graphics** toolbar.

Microphones

Right-click **Back Microphone** and choose **Point Graph**.

Point Graph 1

1 In the **Settings** window for **Point Graph**, locate the **Selection** section.

2 From the **Selection** list, choose **Front Microphone Point**.

3 Locate the **y-Axis Data** section. In the **Expression** text field, type `arg(acpr.p_t)`.

4 Click to expand the **Coloring and Style** section. From the **Color** list, choose **Cycle (reset)**.

5 Find the **Line style** subsection. From the **Line** list, choose **Dashed**.

6 Click to expand the **Legends** section. Select the **Show legends** checkbox.

7 From the **Legends** list, choose **Manual**.

8 In the table, enter the following settings:

Legends
`Front Microphone - Phase`

Point Graph 2

1 Right-click **Results** > **Microphones** > **Point Graph 1** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, locate the **Selection** section.

3 Click to select the **Activate Selection** toggle button.

4 From the **Selection** list, choose **Front Microphone Point**.

5 Locate the **Coloring and Style** section. From the **Color** list, choose **Cycle**.

6 Locate the **Legends** section. In the table, enter the following settings:

Legends
`Back Microphone - Phase`

Microphones

1 In the **Model Builder** window, click **Microphones**.

2 In the **Settings** window for **1D Plot Group**, locate the **Plot Settings** section.

3 Select the **Two y-axes** checkbox.

4 In the table, select the **Plot on secondary y-axis** checkboxes for **Point Graph 1** and **Point Graph 2**.

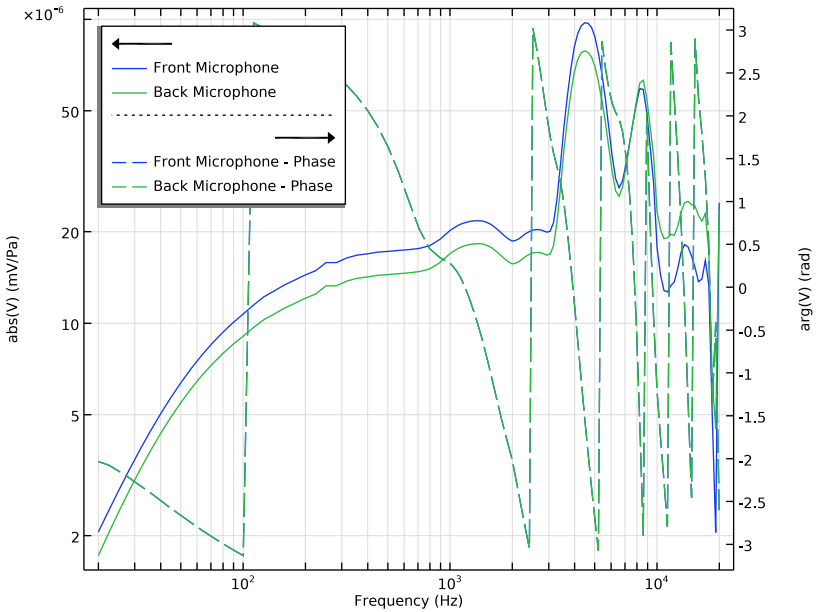
5 Select the **y-axis label** checkbox. In the associated text field, type `abs(V) (mV/Pa)`.

6 Select the **Secondary y-axis label** checkbox. In the associated text field, type `arg(V) (rad)`.

7 Select the **x-axis label** checkbox. In the associated text field, type `Frequency (Hz)`.

8 Locate the **Title** section. From the **Title type** list, choose **None**.

9 In the **Microphones** toolbar, click **Plot**.



Sound Pressure Level (acpr)

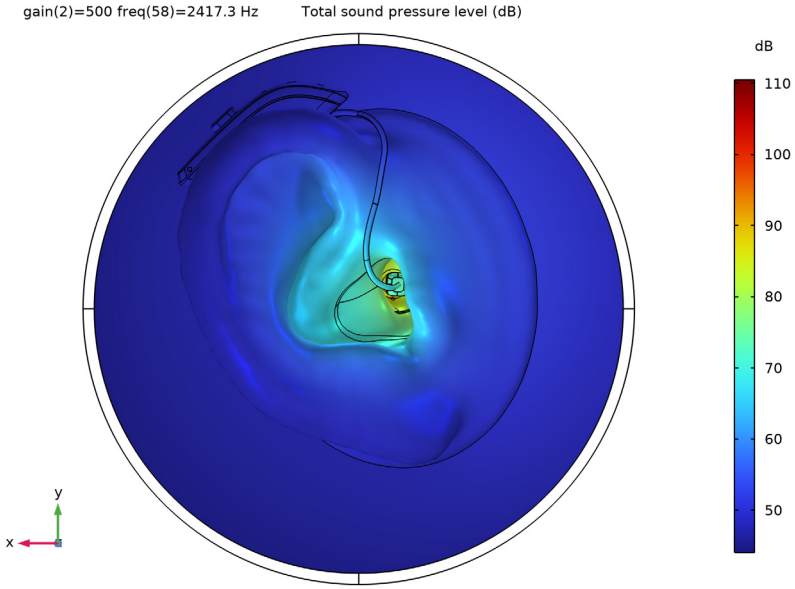
1 In the **Model Builder** window, click **Sound Pressure Level (acpr)**.

2 In the **Settings** window for **3D Plot Group**, locate the **Data** section.

3 From the **Parameter value (freq (Hz))** list, choose **2417.3**.

4 In the **Sound Pressure Level (acpr)** toolbar, click **Plot**.

5 Click the **Show Grid** button in the **Graphics** toolbar.



Sound Pressure Level Array

1 Right-click **Sound Pressure Level (acpr)** and choose **Duplicate**.

2 In the **Settings** window for **3D Plot Group**, type `Sound Pressure Level Array` in the **Label** text field.

3 Locate the **Data** section. From the **Parameter value (gain)** list, choose **0**.

4 Locate the **Color Legend** section. From the **Position** list, choose **Bottom**.

5 Click to expand the **Title** section. From the **Title type** list, choose **None**.

6 Click to expand the **Plot Array** section. From the **Array type** list, choose **Square**.

Surface 1

1 In the **Model Builder** window, expand the **Sound Pressure Level Array** node, then click **Surface 1**.

2 In the **Settings** window for **Surface**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 1/Solution 1 (sol1)**.

Surface 2

1 Right-click **Results** > **Sound Pressure Level Array** > **Surface 1** and choose **Duplicate**.

2 In the **Settings** window for **Surface**, locate the **Data** section.

3 From the **Parameter value (freq (Hz))** list, choose **1995.3**.

4 Click to expand the **Inherit Style** section. From the **Plot** list, choose **Surface 1**.

Surface 3

1 Right-click **Surface 2** and choose **Duplicate**.

2 In the **Settings** window for **Surface**, locate the **Data** section.

3 From the **Parameter value (freq (Hz))** list, choose **200**.

Surface 4

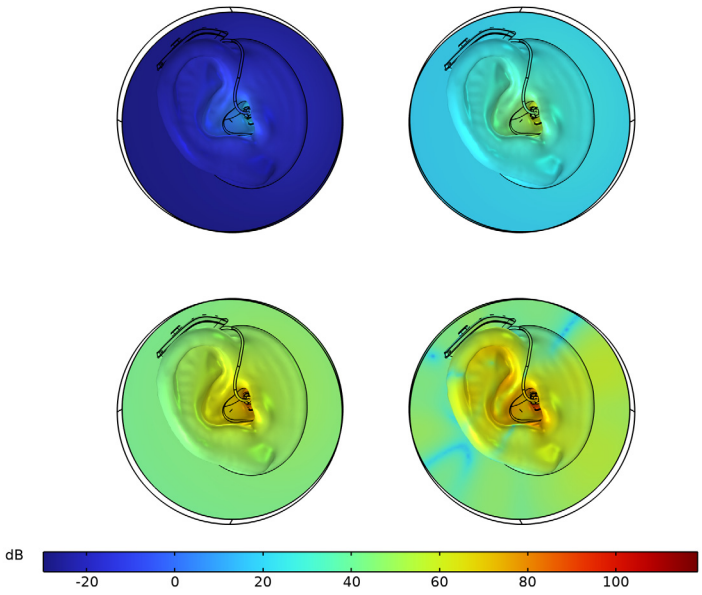
1 Right-click **Surface 3** and choose **Duplicate**.

2 In the **Settings** window for **Surface**, locate the **Data** section.

3 From the **Parameter value (freq (Hz))** list, choose **20**.

4 Click the **Show Axis Orientation** button in the **Graphics** toolbar.

5 In the **Sound Pressure Level Array** toolbar, click **Plot**.

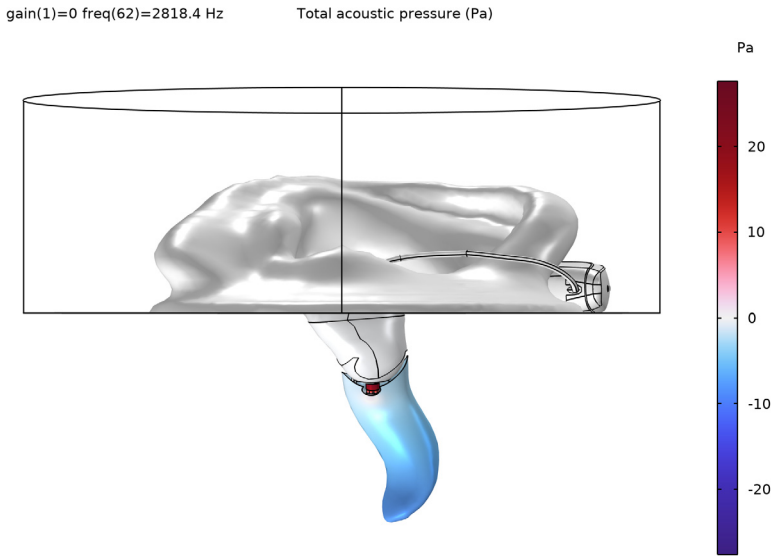


Acoustic Pressure (acpr)

1 In the **Model Builder** window, under **Results** click **Acoustic Pressure (acpr)**.

2 In the **Settings** window for **3D Plot Group**, locate the **Data** section.

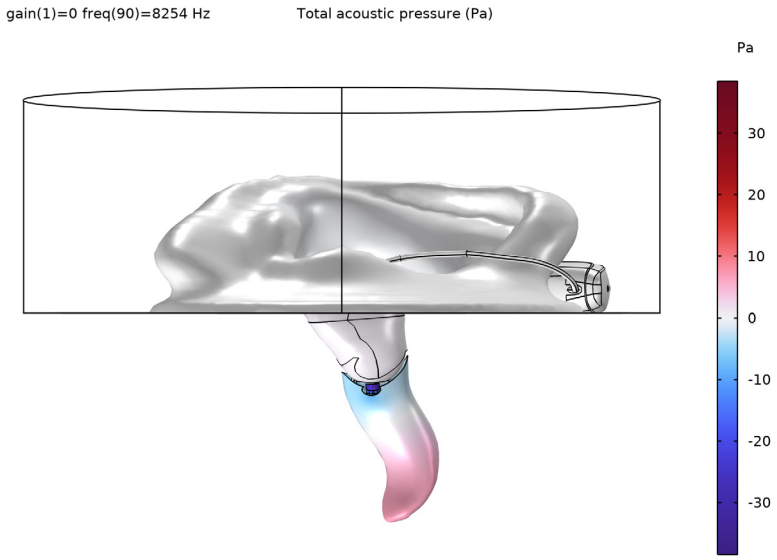
3 From the **Parameter value (gain)** list, choose **0**.



4 In the **Model Builder** window, click **Acoustic Pressure (acpr)**.

5 From the **Parameter value (freq (Hz))** list, choose **14678**.

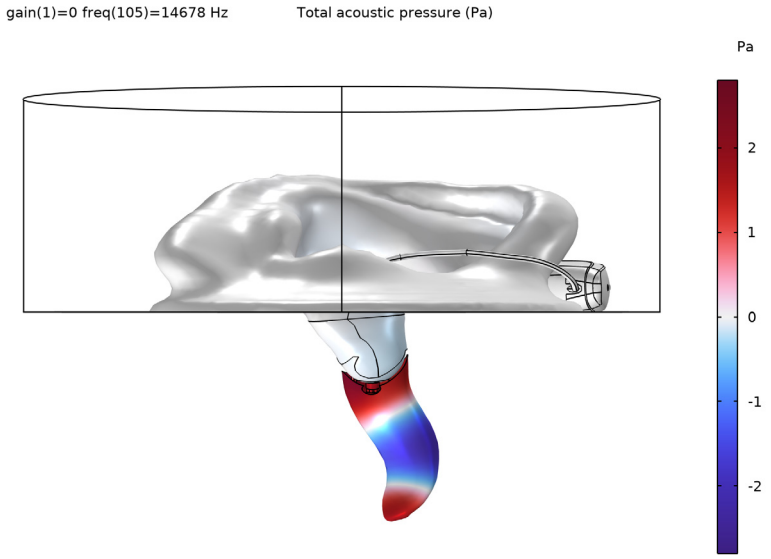
6 In the **Acoustic Pressure (acpr)** toolbar, click **Plot**.



Create a plot of the acoustic response on the eardrum including effects of acoustic feedback.

Acoustic Feedback - Constant Gain

1 In the **Results** toolbar, click **1D Plot Group**.



2 In the **Settings** window for **1D Plot Group**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 1/Parametric Solutions 1 (sol2)**.

4 In the **Label** text field, type `Acoustic Feedback - Constant Gain`.

5 Locate the **Title** section. From the **Title type** list, choose **None**.

6 Locate the **Legend** section. From the **Position** list, choose **Upper left**.

Octave Band 1

1 In the **Acoustic Feedback - Constant Gain** toolbar, click **More Plots** and choose **Octave Band**.

2 In the **Settings** window for **Octave Band**, locate the **Selection** section.

3 From the **Geometric entity level** list, choose **Boundary**.

4 From the **Selection** list, choose **Ear Drum**.

5 Locate the **y-Axis Data** section. In the **Amplitude reference** text field, type `acpr.pref_SPL*sqrt(2)`.

6 Locate the **Plot** section. From the **Quantity** list, choose **Continuous power spectral density**.

7 Locate the **Legends** section. Select the **Show legends** checkbox.

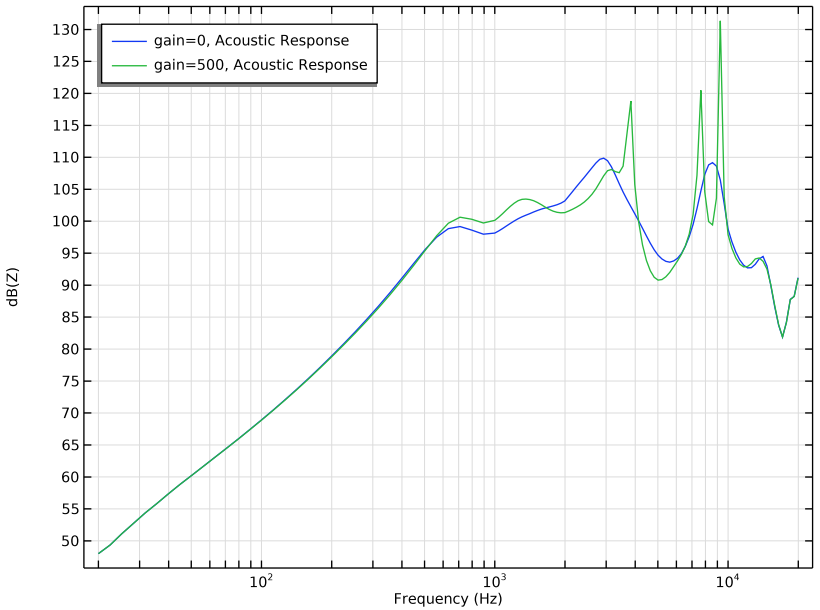
8 Locate the **y-Axis Data** section.

9 Select the **Description** checkbox. In the associated text field, type `Acoustic Response`.

10 In the **Acoustic Feedback - Constant Gain** toolbar, click **Plot**.

Thumbnail

1 In the **Results** toolbar, click **3D Plot Group**.



2 In the **Settings** window for **3D Plot Group**, type `Thumbnail` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 1/ Parametric Solutions 1 (sol2)**.

4 From the **Parameter value (gain)** list, choose **0**.

5 From the **Parameter value (freq (Hz))** list, choose **1847.8**.

6 Locate the **Plot Settings** section. Clear the **Plot dataset edges** checkbox.

7 Locate the **Color Legend** section. Clear the **Show legends** checkbox.

8 Locate the **Title** section. From the **Title type** list, choose **None**.

Intensity

1 Right-click **Thumbnail** and choose **Streamline**.

2 In the **Settings** window for **Streamline**, type `Intensity` in the **Label** text field.

3 Locate the **Expression** section. In the **X-component** text field, type `-acpr.Ix`.

4 In the **Y-component** text field, type `-acpr.Iy`.

5 In the **Z-component** text field, type `-acpr.Iz`.

6 Locate the **Streamline Positioning** section. In the **Number** text field, type `30`.

7 Select Boundary 3 only.

8 Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Type** list, choose **Tube**.

9 Click to expand the **Advanced** section. Clear the **Allow backward time integration** checkbox.

Color Expression 1

1 Right-click **Intensity** and choose **Color Expression**.

2 In the **Settings** window for **Color Expression**, locate the **Expression** section.

3 In the **Expression** text field, type `acpr.I_mag`.

4 Locate the **Coloring and Style** section. From the **Color table** list, choose **Rainbow**.

5 From the **Scale** list, choose **Logarithmic**.

6 Click to expand the **Range** section. Select the **Manual color range** checkbox.

7 In the **Maximum** text field, type `1e-5`.

Ear

1 In the **Model Builder** window, right-click **Thumbnail** and choose **Surface**.

2 In the **Settings** window for **Surface**, type `Ear` in the **Label** text field.

Material Appearance 1

1 Right-click **Ear** and choose **Material Appearance**.

2 In the **Settings** window for **Material Appearance**, locate the **Appearance** section.

3 From the **Appearance** list, choose **Custom**.

4 From the **Color** list, choose **Gray**.

Selection 1

1 In the **Model Builder** window, right-click **Ear** and choose **Selection**.

2 In the **Settings** window for **Selection**, locate the **Selection** section.

3 Click  **Paste Selection**.

4 In the **Paste Selection** dialog, type `5-9, 14, 129` in the **Selection** text field.

5 Click **OK**.

Wire

1 Right-click **Ear** and choose **Duplicate**.

2 In the **Model Builder** window, click **Ear 1**.

3 In the **Settings** window for **Surface**, type `Wire` in the **Label** text field.

Material Appearance 1

1 In the **Model Builder** window, click **Material Appearance 1**.

2 In the **Settings** window for **Material Appearance**, locate the **Appearance** section.

3 From the **Color** list, choose **White**.

Selection 1

1 In the **Model Builder** window, click **Selection 1**.

2 In the **Settings** window for **Selection**, locate the **Selection** section.

3 Click  **Clear Selection**.

4 Click  **Paste Selection**.

5 In the **Paste Selection** dialog, type `44, 45, 135-140, 143, 144` in the **Selection** text field.

6 Click **OK**.

Hearing Aid (Copper)

1 In the **Model Builder** window, right-click **Wire** and choose **Duplicate**.

2 In the **Model Builder** window, click **Wire 1**.

3 In the **Settings** window for **Surface**, type `Hearing Aid (Copper)` in the **Label** text field.

Material Appearance 1

1 In the **Model Builder** window, click **Material Appearance 1**.

2 In the **Settings** window for **Material Appearance**, locate the **Appearance** section.

3 From the **Material type** list, choose **Copper (oxidized)**.

Selection 1

1 In the **Model Builder** window, click **Selection 1**.

2 In the **Settings** window for **Selection**, locate the **Selection** section.

3 Click  **Clear Selection**.

4 Click  **Paste Selection**.

5 In the **Paste Selection** dialog, type `146, 148, 150, 151, 153-155, 157, 159, 160, 162, 163, 165-168, 170-176, 178, 179, 181-189, 191, 194, 195` in the **Selection** text field.

6 Click **OK**.

Hearing Aid (Black)

1 In the **Model Builder** window, right-click **Hearing Aid (Copper)** and choose **Duplicate**.

2 In the **Model Builder** window, click **Hearing Aid (Copper) 1**.

3 In the **Settings** window for **Surface**, type `Hearing Aid (Black)` in the **Label** text field.

Material Appearance 1

1 In the **Model Builder** window, click **Material Appearance 1**.

2 In the **Settings** window for **Material Appearance**, locate the **Appearance** section.

3 From the **Material type** list, choose **Plastic**.

4 From the **Color** list, choose **Black**.

Selection 1

1 In the **Model Builder** window, click **Selection 1**.

2 In the **Settings** window for **Selection**, locate the **Selection** section.

3 Click  **Clear Selection**.

4 Click  **Paste Selection**.

5 In the **Paste Selection** dialog, type `10-13, 15-43, 46-128, 130-134, 145, 147, 149, 152, 156, 158, 164, 177, 180, 190, 192, 193, 196` in the **Selection** text field.

6 Click **OK**.

LED

1 In the **Model Builder** window, right-click **Hearing Aid (Black)** and choose **Duplicate**.

2 In the **Model Builder** window, click **Hearing Aid (Black) 1**.

3 In the **Settings** window for **Surface**, type `LED` in the **Label** text field.

Material Appearance 1

1 In the **Model Builder** window, click **Material Appearance 1**.

2 In the **Settings** window for **Material Appearance**, locate the **Appearance** section.

3 From the **Color** list, choose **Green**.

Selection 1

1 In the **Model Builder** window, click **Selection 1**.

2 In the **Settings** window for **Selection**, locate the **Selection** section.

3 Click  **Clear Selection**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog, type 169 in the **Selection** text field.

6 Click **OK**.

Geometry Modeling Instructions

From the **File** menu, choose **New**.

NEW

In the **New** window, click **Blank Model**.

ADD COMPONENT

In the **Home** toolbar, click **Add Component** and choose **3D**.

GEOMETRY 1

1 In the **Settings** window for **Geometry**, locate the **Units** section.

2 From the **Length unit** list, choose **mm**.

3 Locate the **Advanced** section. From the **Geometry representation** list, choose **CAD kernel**.

In the first geometry part, load the CAD file for a hearing aid cassette and prepare it for the model. Because only the outer shell of the cassette is of interest, remove details of the interior geometry. Simplify the geometry to avoid small features that would require a really fine mesh.

PART 1

1 In the **Model Builder** window, right-click **Global Definitions** and choose **Geometry Parts** > **3D Part**.

2 In the **Settings** window for **Part**, locate the **Units** section.

3 From the **Length unit** list, choose **mm**.

4 Locate the **Advanced** section. From the **Geometry representation** list, choose **CAD kernel**.

5 Select the **Design Module Boolean operations** checkbox.

Import 1 (imp1)

1 In the **Geometry** toolbar, click **Import**.

2 In the **Settings** window for **Import**, locate the **Source** section.

3 Click **Browse**.

4 Browse to the model's Application Libraries folder and double-click the file `full_ear_hearing_aid_ha_body.mphbin`.

5 Click **null**.

Extract 1 (extract1)

1 In the **Geometry** toolbar, click **Extract**.

2 In the **Settings** window for **Extract**, locate the **Entities or Objects to Extract** section.

3 Click the **Paste Selection** button for **Selection**.

4 In the **Paste Selection** dialog, type `imp1: 16-19, 26, 27, 32, 33, 43, 44, 53-56, 65, 67, 687, 688, 1036, 1038, 1063, 1064, 1081, 1082, 1165, 1166, 1174, 1175, 1479, 1480, 1539, 1540, 1722, 1723, 1768, 1769, 1820, 1821, 2133, 2134, 2143, 2144, 2264, 2265, 2357, 2358, 2375, 2423, 2500, 2501, 2655-2659` in the **Selection** text field.

5 Click **OK**.

6 In the **Settings** window for **Extract**, locate the **Entities or Objects to Extract** section.

7 From the **Input object handling** list, choose **Remove**.

8 Click **Build Selected**.

Repair 1 (rep1)

1 In the **Geometry** toolbar, click **Defeaturing and Repair** and choose **Repair**.

2 In the **Settings** window for **Repair**, locate the **Repair** section.

3 In the **Absolute repair tolerance** text field, type `5e-2`.

4 Select the object **extract1** only.

5 Right-click **Repair 1 (rep1)** and choose **Build All Objects**.

Cap Faces 1 (cap1)

1 In the **Geometry** toolbar, click **Defeaturing and Repair** and choose **Cap Faces**.

2 Click the **Zoom Box** button in the **Graphics** toolbar.

3 In the **Settings** window for **Cap Faces**, locate the **Cap Faces** section.

4 Select the **Group adjacent edges** checkbox.

5 On the object **rep1**, select Edges 6–11, 14, 15, 21–26, 42–59, 62–64, 66, 68, 69, 96, 97, 107, 108, 118, 120, 135, 137, 160, and 161 only.

6 Click **Build Selected**.

Line Segment 1 (ls1)

1 In the **Geometry** toolbar, click **More Primitives** and choose **Line Segment**.

2 On the object **cap1**, select Point 61 only.

3 In the **Settings** window for **Line Segment**, locate the **Endpoint** section.

4 Click to select the **Activate Selection** toggle button for **End vertex**.

5 On the object **cap1**, select Point 63 only.

Line Segment 2 (ls2)

1 Right-click **Line Segment 1 (ls1)** and choose **Duplicate**.

2 In the **Settings** window for **Line Segment**, locate the **Starting Point** section.

3 Click to select the **Activate Selection** toggle button for **Start vertex**.

4 In the tree, select **cap1**.

5 On the object **cap1**, select Point 62 only.

6 Locate the **Endpoint** section. Click to select the **Activate Selection** toggle button for **End vertex**.

7 In the tree, select **cap1**.

8 On the object **cap1**, select Point 64 only.

9 Click **Build Selected**.

Union 1 (uni1)

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Union**.

2 Click in the **Graphics** window and then press Ctrl+A to select all objects.

3 In the **Settings** window for **Union**, click **Build Selected**.

Cap Faces 2 (cap2)

1 In the **Geometry** toolbar, click **Defeaturing and Repair** and choose **Cap Faces**.

2 In the **Settings** window for **Cap Faces**, locate the **Cap Faces** section.

3 Select the **Group adjacent edges** checkbox.

4 On the object **uni1**, select Edges 20, 21, 23, 24, 40, 41, 43, 45, 76, 77, 83, and 85 only.

5 Click **Build Selected**.

Cap Faces 3 (cap3)

1 Right-click **Cap Faces 2 (cap2)** and choose **Duplicate**.

2 On the object **cap2**, select Edges 83–86, 88, 90, 92, 94, 99, 100, 119–124, 131–134, 137, and 139 only.

3 In the **Settings** window for **Cap Faces**, click **Build Selected**.

Cap Faces 4 (cap4)

1 Right-click **Cap Faces 3 (cap3)** and choose **Duplicate**.

2 On the object **cap3**, select Edges 1, 2, and 150–153 only.

3 In the **Settings** window for **Cap Faces**, click **Build Selected**.

Cap Faces 5 (cap5)

1 Right-click **Cap Faces 4 (cap4)** and choose **Duplicate**.

2 On the object **cap4**, select Edges 222–227 only.

3 In the **Settings** window for **Cap Faces**, click **Build Selected**.

Convert to Solid 1 (csol1)

1 In the **Geometry** toolbar, click **Conversions** and choose **Convert to Solid**.

2 Select the object **cap5** only.

3 In the **Settings** window for **Convert to Solid**, click **Build Selected**.

Work Plane 1 (wp1)

1 In the **Geometry** toolbar, click **Work Plane**.

2 In the **Settings** window for **Work Plane**, locate the **Plane Definition** section.

3 From the **Plane type** list, choose **Normal vector**.

4 Find the **Normal vector** subsection. In the **x** text field, type `-1`.

5 In the **y** text field, type `0.6`.

6 In the **z** text field, type `0`.

7 Find the **Point on plane** subsection. In the **x** text field, type `-6.5`.

8 Click **Build Selected**.

Partition Domains 1 (pard1)

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Partition Domains**.

2 On the object **csol1**, select Domain 1 only.

3 In the **Settings** window for **Partition Domains**, click **Build Selected**.

Delete Entities 1 (del1)

1 In the **Model Builder** window, right-click **Part 1** and choose **Delete Entities**.

2 In the **Settings** window for **Delete Entities**, locate the **Entities or Objects to Delete** section.

3 From the **Geometric entity level** list, choose **Domain**.

4 On the object **pard1**, select Domain 1 only.

5 Click **Build Selected**.

Delete Entities 2 (del2)

1 Right-click **Part 1** and choose **Delete Entities**.

2 On the object **del1**, select Boundaries 9, 10, 60–63, and 65 only.

3 In the **Settings** window for **Delete Entities**, click **Build Selected**.

Ignore Edges 1 (ige1)

1 In the **Geometry** toolbar, click **Virtual Operations** and choose **Ignore Edges**.

2 On the object **fin**, select Edges 5, 14, 15, 20, 31, 67, 69, 76, 109, 137, 145, 158, 163, and 174 only.

3 In the **Geometry** toolbar, click **Build All**.

Remove Details 1 (rmd1)

1 In the **Geometry** toolbar, click **Virtual Operations** and choose **Remove Details**.

2 Click **Build All**.

In the second geometry part, load and prepare the CAD file for the in-ear hearing aid. Remove details and define a work plane to use when aligning the hearing aid with the ear.

EAR BUD

1 In the **Model Builder** window, under **Global Definitions** right-click **Geometry Parts** and choose **3D Part**.

2 In the **Settings** window for **Part**, type `Ear bud` in the **Label** text field.

3 Locate the **Units** section. From the **Length unit** list, choose **mm**.

4 Locate the **Advanced** section. From the **Geometry representation** list, choose **CAD kernel**.

5 Select the **Design Module Boolean operations** checkbox.

Import 1 (imp1)

1 In the **Geometry** toolbar, click **Import**.

2 In the **Settings** window for **Import**, locate the **Source** section.

3 Click **Browse**.

4 Browse to the model's Application Libraries folder and double-click the file `full_ear_hearing_aid_rie.mphbin`.

5 Click **null**.

Work Plane 1 (wp1)

1 In the **Geometry** toolbar, click **Work Plane**.

2 In the **Settings** window for **Work Plane**, locate the **Plane Definition** section.

3 From the **Plane type** list, choose **Face parallel**.

4 On the object **imp1**, select Boundary 222 only.

Partition Domains 1 (pard1)

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Partition Domains**.

2 In the **Settings** window for **Partition Domains**, locate the **Partition Domains** section.

3 From the **Partition with** list, choose **Extended faces**.

4 Click to select the **Activate Selection** toggle button for **Domains to partition**.

5 On the object **imp1**, select Domain 2 only.

6 Click to select the **Activate Selection** toggle button for **Planar, cylindrical, or spherical faces**.

7 On the object **imp1**, select Boundary 34 only.

8 Click **Build Selected**.

Delete Entities 1 (del1)

1 In the **Model Builder** window, right-click **Ear bud** and choose **Delete Entities**.

2 In the **Settings** window for **Delete Entities**, locate the **Entities or Objects to Delete** section.

3 From the **Geometric entity level** list, choose **Domain**.

4 On the object **pard1**, select Domain 3 only.

5 Click **Build Selected**.

Partition Domains 2 (pard2)

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Partition Domains**.

2 On the object **del1**, select Domain 9 only.

3 In the **Settings** window for **Partition Domains**, locate the **Partition Domains** section.

4 From the **Partition with** list, choose **Extended faces**.

5 On the object **del1**, select Boundaries 184 and 195 only.

6 In the **Geometry** toolbar, click **Build All**.

Collapse Faces 1 (clf1)

1 In the **Geometry** toolbar, click **Virtual Operations** and choose **Collapse Faces**.

2 On the object **fin**, select Boundaries 63, 65, 109, 126, 129, 181, 188, 236, and 247 only.

3 In the **Geometry** toolbar, click **Build All**.

Ignore Edges 1 (ige1)

1 In the **Geometry** toolbar, click **Virtual Operations** and choose **Ignore Edges**.

2 On the object **clf1**, select Edges 11, 18, 23, 24, 39, 45, 109, 121, 159, 186, 187, 198, 244, 267, 278, and 300 only.

3 In the **Geometry** toolbar, click **Build All**.

Remove Details 1 (rmd1)

1 In the **Geometry** toolbar, click **Virtual Operations** and choose **Remove Details**.

2 Click **Build All**.

The next step is to combine the two parts of the hearing aid with the model of the full ear.

GEOMETRY 1

Import 1 (imp1)

1 In the **Geometry** toolbar, click **Import**.

2 In the **Settings** window for **Import**, locate the **Source** section.

3 Click **Browse**.

4 Browse to the model's Application Libraries folder and double-click the file `full_ear_hearing_aid_full_ear.mphbin`.

5 Click **null**.

6 Locate the **Virtual Geometry** section. Clear the **Include result from virtual operations** checkbox.

7 Click **Build Selected**.

DEFINITIONS

In the **Model Builder** window, expand the **Component 1 (comp1)** > **Definitions** node.

Hide for Geometry 1

1 In the **Model Builder** window, expand the **Component 1 (comp1)** > **Definitions** > **View 1** node.

2 Right-click **View 1** and choose **Hide for Geometry**.

3 In the **Settings** window for **Hide for Geometry**, locate the **Selection** section.

4 From the **Geometric entity level** list, choose **Boundary**.

5 On the object **imp1**, select Boundaries 1, 2, 4, 26, and 46 only.

GEOMETRY 1

Part Instance 1 (pi1)

1 In the **Geometry** toolbar, click  **Part Instance** and choose **Part 1**.

2 In the **Settings** window for **Part Instance**, locate the **Position and Orientation of Output** section.

3 Find the **Displacement** subsection. In the **xwi** text field, type `111`.

4 In the **ywi** text field, type `75.3`.

5 In the **zwi** text field, type `72`.

6 Find the **Rotation** subsection. From the **Specify** list, choose **Euler angles (Z-X-Z)**.

7 In the β text field, type `80`.

8 In the γ text field, type `58`.

9 Click  **Build Selected**.

Work Plane 1 (wp1)

1 In the **Geometry** toolbar, click  **Work Plane**.

2 In the **Settings** window for **Work Plane**, locate the **Plane Definition** section.

3 From the **Plane type** list, choose **Normal vector**.

4 Find the **Normal vector** subsection. In the **x** text field, type `0.4`.

5 In the **y** text field, type `-2`.

6 In the **z** text field, type `0.4`.

7 Find the **Point on plane** subsection. In the **x** text field, type `110`.

8 In the **y** text field, type `59`.

9 In the **z** text field, type `40.1`.

10 Click  **Build Selected**.

Ear bud 1 (pi2)

1 In the **Geometry** toolbar, click  **Part Instance** and choose **Ear bud**.

2 In the **Settings** window for **Part Instance**, locate the **Position and Orientation of Output** section.

3 Find the **Coordinate system in part** subsection. From the **Work plane in part** list, choose **Work Plane 1 (wp1)**.

4 Find the **Coordinate system to match** subsection. From the **Work plane** list, choose **Work Plane 1 (wp1)**.

5 Find the **Displacement** subsection. In the **xwi** text field, type `-5.25`.

6 In the **ywi** text field, type `-6.5`.

7 In the **zwi** text field, type `2.1`.

8 Find the **Rotation** subsection. In the **Rotation angle** text field, type `100`.

9 Click **Build Selected**.

Work Plane 2 (wp2)

1 In the **Geometry** toolbar, click **Work Plane**.

2 In the **Settings** window for **Work Plane**, locate the **Plane Definition** section.

3 From the **Plane type** list, choose **Face parallel**.

4 On the object **pi1**, select Boundary 1 only.

The hearing aid cassette is connected to the in-ear hearing aid by a wire. To do this, define three points to create a work plane in which you can draw a line that the wire will follow.

Point 1 (pt1)

1 In the **Geometry** toolbar, click **More Primitives** and choose **Point**.

2 In the **Settings** window for **Point**, locate the **Coordinate System** section.

3 From the **Work plane** list, choose **Work Plane 2 (wp2)**.

Partition Edges 1 (pare1)

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Partition Edges**.

2 On the object **pi2**, select Edge 54 only.

Point 2 (pt2)

1 In the **Geometry** toolbar, click **More Primitives** and choose **Point**.

2 In the **Settings** window for **Point**, locate the **Point** section.

3 In the **x** text field, type `90`.

4 In the **y** text field, type `85`.

5 In the **z** text field, type `60`.

6 Click **Build All Objects**.

Work Plane 3 (wp3)

1 In the **Geometry** toolbar, click **Work Plane**.

2 In the **Settings** window for **Work Plane**, locate the **Plane Definition** section.

3 From the **Plane type** list, choose **Vertices**.

4 On the object **pt1**, select Point 1 only.

5 Click to select the **Activate Selection** toggle button for **Second vertex**.

6 On the object **pt2**, select Point 1 only.

7 Click to select the **Activate Selection** toggle button for **Third vertex**.

8 On the object **pare1**, select Point 201 only.

Work Plane 3 (wp3) > Plane Geometry

In the **Model Builder** window, click **Plane Geometry**.

Work Plane 3 (wp3) > Interpolation Curve 1 (ic1)

1 In the **Work Plane** toolbar, click **More Primitives** and choose **Interpolation Curve**.

2 In the **Settings** window for **Interpolation Curve**, locate the **Interpolation Points** section.

3 In the table, enter the following settings:

xw (mm)	yw (mm)
0	0
6	1
7.5	2.5
9	6
10.5	10.5
10.981909165939186	12.299902459598535

4 Click **Build Selected**.

After drawing the line the `Sweep` node is used to sweep one boundary along the line and connect to the two parts of the hearing aid.

Sweep 1 (swe1)

1 In the **Model Builder** window, right-click **Geometry 1** and choose **Sweep**.

2 On the object **pare1**, select Boundaries 156 and 162 only.

3 In the **Settings** window for **Sweep**, locate the **Spine Curve** section.

4 Click to select the **Activate Selection** toggle button for **Edges to follow**.

5 On the object **wp3**, select Edge 1 only.

6 Find the **Alignment at end** subsection. Select the **Make spine perpendicular to entities** checkbox.

7 On the object **pi1**, select Boundary 1 only.

8 In the **Adjustment parameter length** text field, type `1`.

9 Find the **Alignment at start** subsection. Select the **Make spine perpendicular to entities to sweep** checkbox.

10 In the **Adjustment parameter length** text field, type `0.3`.

11 Select the **Manual control of sweep direction** checkbox.

12 Select the **Reverse direction** checkbox.

13 Click **Build Selected**.

Because the model only uses the air domain, use a union between the different objects and delete the hearing aid, wire, and cassette. Thus, the geometry only contains the air domain.

Union 1 (uni1)

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Union**.

2 Select the objects **pi1** and **swe1** only.

3 In the **Settings** window for **Union**, click **Build Selected**.

4 Locate the **Union** section. Click to select the **Activate Selection** toggle button for **Input objects**.

5 Select the objects **pare1**, **pi1**, and **swe1** only.

6 Click **Build Selected**.

Union 2 (uni2)

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Union**.

2 Select the objects **imp1** and **uni1** only.

3 In the **Settings** window for **Union**, click **Build Selected**.

Delete Entities 1 (del1)

1 Right-click **Geometry 1** and choose **Delete Entities**.

2 In the **Settings** window for **Delete Entities**, locate the **Entities or Objects to Delete** section.

3 From the **Geometric entity level** list, choose **Domain**.

4 On the object **uni2**, select Domains 2–7, 9–13, 22–25, 28–30, 32, and 33 only.

5 Click **Build Selected**.

Work Plane 4 (wp4)

1 In the **Geometry** toolbar, click  **Work Plane**.

2 In the **Settings** window for **Work Plane**, locate the **Plane Definition** section.

3 From the **Plane type** list, choose **Face parallel**.

4 On the object **del1**, select Boundary 3 only.

Rigid Transform 1 (rt1)

1 In the **Geometry** toolbar, click  **Transforms** and choose **Rigid Transform**.

2 Select the object **del1** only.

3 In the **Settings** window for **Rigid Transform**, locate the **Coordinate System for Objects** section.

4 From the **Work plane for objects** list, choose **Work Plane 4 (wp4)**.

5 Click  **Build Selected**.

Delete Entities 2 (del2)

1 Right-click **Geometry 1** and choose **Delete Entities**.

2 Click in the **Graphics** window and then press Ctrl+D to clear all objects.

3 In the **Settings** window for **Delete Entities**, locate the **Entities or Objects to Delete** section.

4 From the **Geometric entity level** list, choose **Object**.

5 Select the objects **pt1**, **pt2**, and **wp3** only.

Create selections to make it simpler to add features to the correct domains and surfaces.

Speaker

1 In the **Geometry** toolbar, click  **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Speaker` in the **Label** text field.

3 Locate the **Entities to Select** section. From the **Geometric entity level** list, choose **Boundary**.

4 On the object **rt1**, select Boundary 117 only.

Front Microphone

1 In the **Geometry** toolbar, click  **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Front Microphone` in the **Label** text field.

3 Locate the **Entities to Select** section. From the **Geometric entity level** list, choose **Boundary**.

4 On the object **rt1**, select Boundary 230 only.

Back Microphone

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Back Microphone` in the **Label** text field.

3 Locate the **Entities to Select** section. From the **Geometric entity level** list, choose **Boundary**.

4 On the object **rt1**, select Boundary 255 only.

Microphones

1 In the **Geometry** toolbar, click **Selections** and choose **Union Selection**.

2 In the **Settings** window for **Union Selection**, type `Microphones` in the **Label** text field.

3 Locate the **Geometric Entity Level** section. From the **Level** list, choose **Boundary**.

4 Locate the **Input Entities** section. Click **Add**.

5 In the **Add** dialog, in the **Selections to add** list, choose **Front Microphone** and **Back Microphone**.

6 Click **OK**.

7 In the **Settings** window for **Union Selection**, click **Build Selected**.

Ear Drum

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Ear Drum` in the **Label** text field.

3 Locate the **Entities to Select** section. From the **Geometric entity level** list, choose **Boundary**.

4 On the object **rt1**, select Boundaries 193 and 194 only.

Ear Canal - TVBLI Boundaries

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Ear Canal - TVBLI Boundaries` in the **Label** text field.

3 Locate the **Entities to Select** section. From the **Geometric entity level** list, choose **Boundary**.

4 On the object **rt1**, select Boundaries 30–32, 34, 42, 48, 61–63, 67, 85, 111, 120, 127, 129, 185–188, and 210 only.

Front Microphone Point

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Front Microphone Point` in the **Label** text field.

3 Locate the **Entities to Select** section. From the **Geometric entity level** list, choose **Point**.

4 On the object **rt1**, select Point 401 only.

Back Microphone Point

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Back Microphone Point` in the **Label** text field.

3 Locate the **Entities to Select** section. From the **Geometric entity level** list, choose **Point**.

4 On the object **rt1**, select Point 467 only.

Form Union (fin)

In the **Geometry** toolbar, click **Build All**.

Vent Holes

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Vent Holes` in the **Label** text field.

3 On the object **fin**, select Domains 7 and 13 only.

Wax Guard Holes

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Wax Guard Holes` in the **Label** text field.

3 On the object **fin**, select Domains 4, 5, and 8–12 only.

Ear-Bud Domain

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Ear-Bud Domain` in the **Label** text field.

3 On the object **fin**, select Domains 3 and 6 only.

Finally, clean up the model by collapsing thin faces, merging edges, and removing vertices. This helps to avoid creating too small mesh elements when meshing the geometry.

Form Composite Faces 1 (cmf1)

1 In the **Geometry** toolbar, click **Virtual Operations** and choose **Form Composite Faces**.

2 On the object **fin**, select Boundaries 19 and 183 only.

3 In the **Settings** window for **Form Composite Faces**, click **Build Selected**.

Collapse Faces 1 (clf1)

1 In the **Geometry** toolbar, click **Virtual Operations** and choose **Collapse Faces**.

2 On the object **cmf1**, select Boundaries 19, 204, and 207 only.

3 In the **Settings** window for **Collapse Faces**, click **Build Selected**.

Ear

1 In the **Geometry** toolbar, click **Virtual Operations** and choose **Form Composite Faces**.

2 In the **Settings** window for **Form Composite Faces**, type `Ear` in the **Label** text field.

3 On the object **clf1**, select Boundaries 5–16, 19–21, 26, 78, 161, 183, 212, 214, 217, 218, 220, 225, 235–238, 242, 243, 249–251, and 257–259 only.

4 Click **Build Selected**.

Ear drum

1 Right-click **Ear** and choose **Duplicate**.

2 In the **Settings** window for **Form Composite Faces**, type `Ear drum` in the **Label** text field.

3 Locate the **Input** section. From the **Faces to composite** list, choose **Ear Drum**.

4 Click **Build Selected**.

Ear canal

1 Right-click **Ear drum** and choose **Duplicate**.

2 In the **Settings** window for **Form Composite Faces**, type `Ear canal` in the **Label** text field.

3 On the object **cmf3**, select Boundaries 19, 35, and 142–144 only.

4 Click **Build Selected**.

Ear bud

1 In the **Geometry** toolbar, click **Virtual Operations** and choose **Form Composite Faces**.

2 In the **Settings** window for **Form Composite Faces**, type `Ear bud` in the **Label** text field.

3 On the object **cmf4**, select Boundaries 11–18, 28, 34, 35, 52, 53, 62, 104, 116, 138, 139, 157, 159, 161, and 165 only.

4 Click **Build Selected**.

Form Composite Faces 6 (cmf6)

1 In the **Geometry** toolbar, click **Virtual Operations** and choose **Form Composite Faces**.

2 On the object **cmf5**, select Boundaries 15, 16, 27, 28, 33, 34, 37–39, 48, 70, 77, 110, 122, 124, 125, 136, 139, 142, and 143 only.

3 In the **Geometry** toolbar, click **Build All**.

Collapse Edges 1 (cle1)

1 In the **Geometry** toolbar, click **Virtual Operations** and choose **Collapse Edges**.

2 On the object **cmf6**, select Edges 180, 241, 296, 297, 327, 332, 333, and 337 only.

3 In the **Geometry** toolbar, click **Build All**.

4 Click the **Go to Default View** button in the **Graphics** toolbar.