Created in COMSOL Multiphysics 6.2

Baffled Piston Radiation

Introduction

An axisymmetric model of a rigid piston in an infinite baffle is used to exemplify the Acoustics Module's Exterior Field Calculation feature. The radiation results obtained with COMSOL Multiphysics are compared with analytical results for the on-axis radiation pattern (as a function of distance), the spatial far-field response, and the total radiated power. The transition from near field to far field is smooth and continuous.

Model Definition

The model consists of a 2D axisymmetric piston recessed in a rigid baffle and vibrating in air. The piston radius is a = 0.1 m. It will be assumed to move at a constant velocity of u_0 = 1 m/s

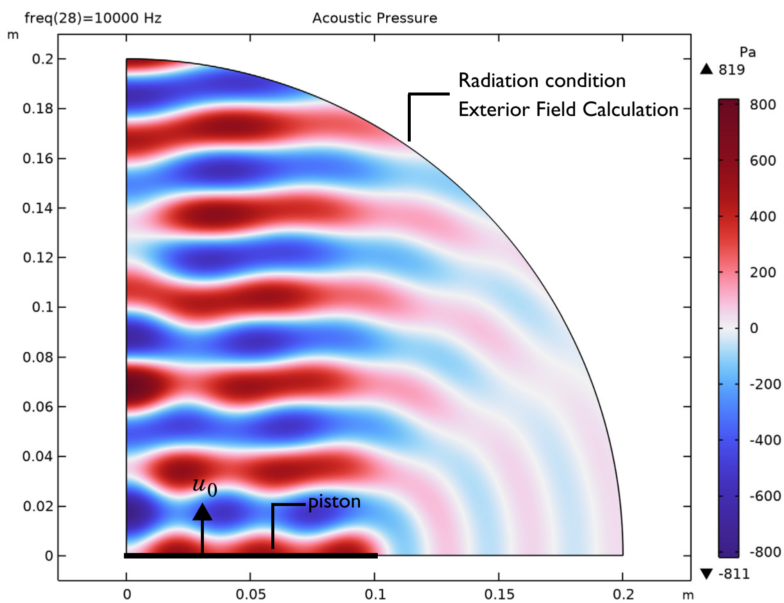


Figure 1: Geometry of the piston in an infinite baffle model. The colors represent the acoustic pressure in the air surrounding the piston at f = 10 kHz.

The piston will be excited in a range of frequencies going from 10 Hz to 20 kHz. The model parameters are given in Table 1.

TABLE 1: MODEL PARAMETERS.

NAME	EXPRESSION	DESCRIPTION
u0	1[m/s]	Piston velocity amplitude
a	0.1[m]	Piston radius
Rmodel	0.2[m]	Domain radius
f0	20000[Hz]	Maximum frequency
c0	343[m/s]	Speed of sound
lam0	c0/f0	Wavelength at f0
ka0	2*pi*a/lam0	k0*a
R0	ka0*a/2	Rayleigh distance at f0
Rfar	20*Rmodel	Far-field evaluation distance
scale	a/lam0	Help variable

As described in Jacobsen and others (Ref. 2), theoretically, the piston can be modeled as a group of uncorrelated monopoles. Supposing linear superposition, the pressure radiated by the piston can be calculated at any point of interest as an integration of the power radiated by a monopole over the surface of the piston:

$$p = i\omega\int_S \frac{e^{i(\omega t - kx)}}{2\pi x} u_0 dS \tag{1}$$

Here, ω is the angular frequency, ρ the density, k the wave number, S the surface of the piston, and x the distance between the point of interest and the running position on the piston. This is a special case of the Rayleigh integral.

The Exterior Field Calculation feature uses the full Kirchhoff–Helmholtz integral, which is valid at any point outside the computational domain. When applied to a flat surface it reduces to the Rayleigh integral.

FAR FIELD

As explained in Jacobsen and others (Ref. 2), the pressure in the far-field approximation can be written using Bessel functions $J_0(z)$ and $J_1(z)$, giving

$$p(r, \theta) = \frac{i\omega\rho u_0}{r}\frac{aJ_1(ka\sin(\theta))}{k\sin(\theta)}e^{i(\omega t - kr)} \tag{2}$$

where θ is the polar angle and r the distance from the center of the piston.

NEAR FIELD

In the near-field approximation, it is not possible to derive an analytical expression for the pressure. However, the force exerted on the piston (or the radiation impedance) can be calculated and is presented in Ref. 1. In the analytical force expression, there is a need to introduce Bessel and Struve functions. The Struve function can be approximated by (see Ref. 3)

$$K_1(2ka) = \frac{2}{\pi} - J_0(2ka) + \left(\frac{16}{\pi} - 5\right)\frac{\sin(2ka)}{2ka} + \left(12 - \frac{36}{\pi}\right)\frac{(1-\cos(2ka))}{(2ka)^2} \tag{3}$$

(The Struve function is also often denoted H_1.) The force on the piston can then be written as

$$F = \rho c \pi a^2 u_0 e^{i\omega t}\left(1 - \frac{J_1(2ka)}{ka} + i\frac{K_1(2ka)}{ka}\right) \tag{4}$$

which by division with the velocity and area gives the radiation impedance. The analytical expressions given above are implemented using variable definitions and integration coupling operators.

Figure 2 shows the computed COMSOL on-axis pressure as well as the analytical results, the asymptotes M and MM, and the far-field limit. First, it is noticeable that the COMSOL and analytical results are really similar.

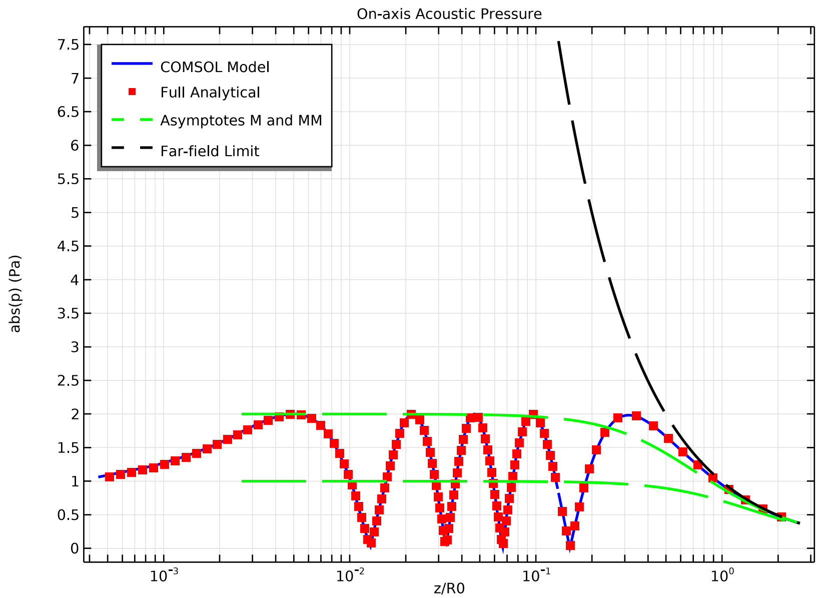


Figure 2: On-axis pressure as a function of z/R_0 (logarithmic axis).

From a theoretical aspect, the pressure nulls in Figure 2 can be explained with the so-called monopole model. All the monopoles will interfere destructively and cancel out, resulting in the pressure being null. According to Blackstock (Ref. 1), the number of nulls, n, depends on the value of a/λ. If this ratio is an integer, then $n = a/\lambda$ and the first null is at the piston itself. If it is not an integer, then $n = \lfloor a/\lambda \rfloor$ (where $\lfloor \ldots \rfloor$ means "the integer part of") and the first null happens in front of the piston.

The asymptotes are also worth noticing. There is good agreement between the COMSOL model and the far-field limit. The asymptotes M and MM represent the following functions (see Ref. 1):

$$|p|_M = \frac{2p_0}{\sqrt{1+\left(\frac{2r}{R_0}\right)^2}} \qquad |p|_{MM} = \frac{p_0}{\sqrt{1+\left(\frac{r}{R_0}\right)^2}} \tag{5}$$

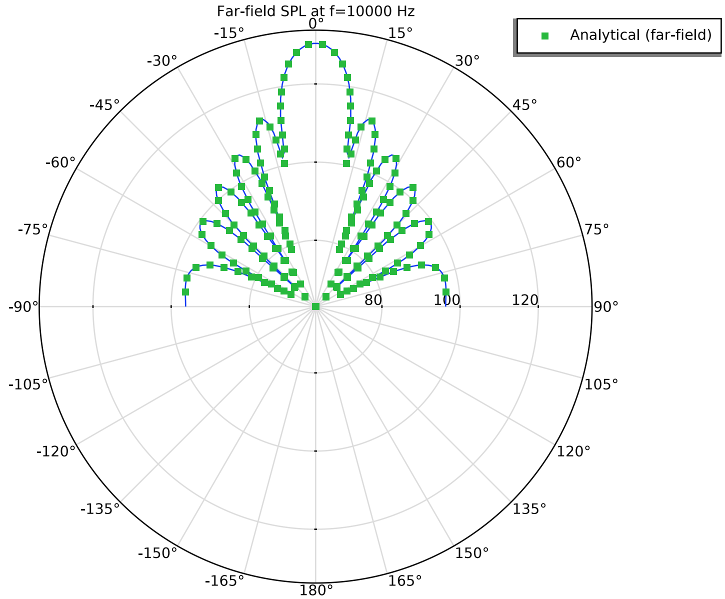


Figure 3: Far-field radiation pattern at f = 10 kHz.

In Figure 3, the radiation pattern of the actual far field, further away than the Rayleigh distance R_0, is plotted at f = 10 kHz. As expected, it shows strong directivity at this frequency; there is a clear focus in the on-axial direction. However, there are still some sidelobes present in other directions. It should be noted that at low frequencies, the piston can behave as a strictly omnidirectional source, because, according to the representation by monopoles, they would all move in phase. Figure 3 also shows good agreement between the simulated and analytical solutions.

In Figure 4, the analytical total radiated power is compared with the result of the COMSOL simulation. They have really similar results from low to high frequencies. It goes from no radiated power to a maximum for the critical frequency before decreasing again to reach a steady state.

Finally, Figure 5 represents the acoustic field created by the piston, both in the computational domain and exterior to the domain. This is achieved using the Exterior Field Calculation feature combined with visualization in a Grid 2D dataset. The feature allows the calculation and the visualization of the pressure field outside the computational domain at any distance including amplitude and phase.

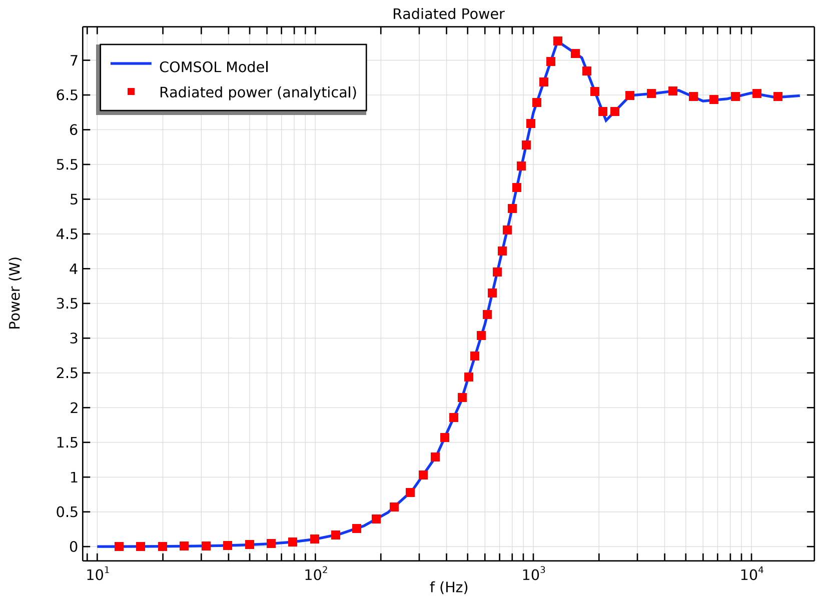


Figure 4: Total radiated power as a function of frequency.

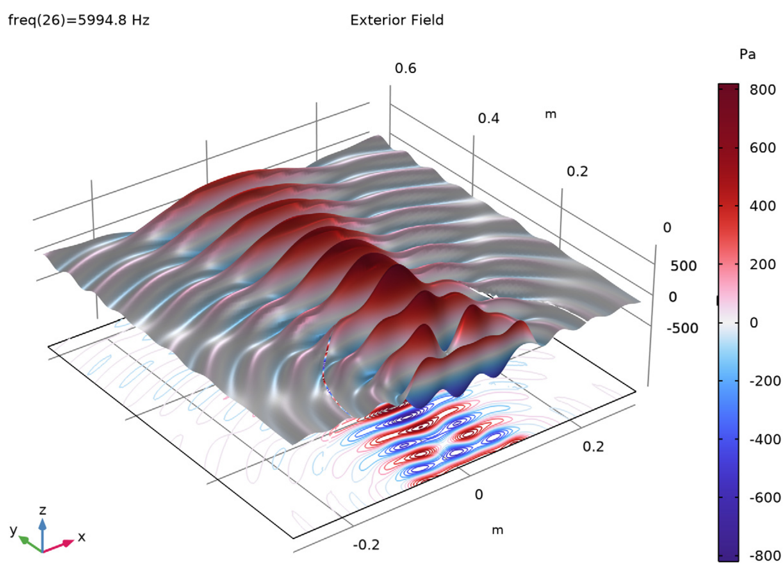


Figure 5: Pressure field near the piston surface.

References

1. D. Blackstock, "Fundamentals of physical acoustics," Wiley-interscience, 2000.

2. F. Jacobsen, T. Poulsen, J.H. Rindel, A.C. Gade, and M. Ohlrich, *Fundamentals of Acoustics and Noise Control*, Technical University of Denmark, Department of Electrical Engineering, 2008.

3. R.M. Aerts and A.J.E.M. Janssen, "Efficient approximation of the Struve functions Hn occurring in the calculation of sound radiation quantities," *J. Acoust. Soc. Am.*, vol. 140, pp. 4154–4160, 2016.

Application Library path: `Acoustics_Module/Verification_Examples/baffled_piston_radiation`

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 **2D Axisymmetric**.
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

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 `baffled_piston_radiation_parameters.txt`.

GEOMETRY 1

Circle 1 (c1)

1. In the **Geometry** toolbar, click **Circle**.
2. In the **Settings** window for **Circle**, locate the **Size and Shape** section.
3. In the **Radius** text field, type `Rmodel`.
4. In the **Sector angle** text field, type `90`.

Point 1 (pt1)

1. In the **Geometry** toolbar, click **Point**.
2. In the **Settings** window for **Point**, locate the **Point** section.
3. In the **r** text field, type `a`.
4. Click **Build All Objects**.

DEFINITIONS

Variables: Analytical Pressure Field

1. In the **Home** toolbar, click **Variables** and choose **Local Variables**.
2. In the **Settings** window for **Variables**, type `Variables: Analytical Pressure Field` in the **Label** text field.
3. Locate the **Variables** section. Click **Load from File**.
4. Browse to the model's Application Libraries folder and double-click the file `baffled_piston_radiation_variables1.txt`.

Variables: Surface Impedance and Power

1. In the **Home** toolbar, click **Variables** and choose **Local Variables**.
2. In the **Settings** window for **Variables**, type `Variables: Surface Impedance and Power` in the **Label** text field.
3. Locate the **Variables** section. Click **Load from File**.
4. Browse to the model's Application Libraries folder and double-click the file `baffled_piston_radiation_variables2.txt`.

Integration 1 (intop1)

1. In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Integration**.
2. In the **Settings** window for **Integration**, type `intop_pt` in the **Operator name** text field.

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

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog box, type 1 in the **Selection** text field.

6 Click **OK**.

7 In the **Settings** window for **Integration**, locate the **Advanced** section.

8 Clear the **Compute integral in revolved geometry** check box.

Integration 2 (intop2)

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

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

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

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog box, type 4 in the **Selection** text field.

6 Click **OK**.

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 **Add to Component** in the window toolbar.

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

PRESSURE ACOUSTICS, FREQUENCY DOMAIN (ACPR)

Pressure Acoustics 1

1 In the **Model Builder** window, under **Component 1 (comp1)>Pressure Acoustics, Frequency Domain (acpr)** click **Pressure Acoustics 1**.

2 In the **Settings** window for **Pressure Acoustics**, locate the **Pressure Acoustics Model** section.

3 From the **Fluid model** list, choose **Atmosphere attenuation**.

Normal Velocity 1

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

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

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog box, type 2 in the **Selection** text field.

5 Click **OK**.

6 In the **Settings** window for **Normal Velocity**, locate the **Normal Velocity** section.

7 In the v_n text field, type u0.

Spherical Wave Radiation 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Spherical Wave Radiation**.

2 In the **Settings** window for **Spherical Wave Radiation**, locate the **Boundary Selection** section.

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog box, type 4 in the **Selection** text field.

5 Click **OK**.

Exterior Field Calculation 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Exterior Field Calculation**.

2 In the **Settings** window for **Exterior Field Calculation**, locate the **Boundary Selection** section.

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog box, type 4 in the **Selection** text field.

5 Click **OK**.

6 In the **Settings** window for **Exterior Field Calculation**, locate the **Exterior Field Calculation** section.

7 From the **Condition in the z = z_0 plane** list, choose **Symmetric/ Infinite sound hard boundary**.

STUDY 1

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

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

3 Clear the **Generate default plots** check box.

Step 1: Frequency Domain

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 Click **Range**.

4 In the **Range** dialog box, choose **Logarithmic** from the **Entry method** list.

5 In the **Start** text field, type `10`.

6 In the **Stop** text field, type `20000`.

7 In the **Steps per decade** text field, type `9`.

8 Click **Replace**.

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

10 From the **Reuse solution from previous step** list, choose **Yes**.

Solution 1 (sol1)

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

MESH 1

In the **Model Builder** window, under **Component 1 (comp1)** right-click **Mesh 1** and choose **Build All**.

STUDY 1

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

RESULTS

In the **Model Builder** window, expand the **Results** node.

Parameterized Curve 2D 1

1 In the **Model Builder** window, expand the **Results>Datasets** node.

2 Right-click **Results>Datasets** and choose **More 2D Datasets>Parameterized Curve 2D**.

3 In the **Settings** window for **Parameterized Curve 2D**, locate the **Parameter** section.

4 In the **Maximum** text field, type `pi/2`.

5 Locate the **Expressions** section. In the **r** text field, type `1.3*a*cos(s)`.

6 In the **z** text field, type `1.3*a*sin(s)`.

Parameterized Curve 2D 2

1 In the **Results** toolbar, click **More Datasets** and choose **Parameterized Curve 2D**.

2 In the **Settings** window for **Parameterized Curve 2D**, locate the **Expressions** section.

3 In the **z** text field, type `1.01*Rmodel*(1-s)+Rfar*s`.

4 Select the **Only evaluate globally defined expressions** check box.

Parameterized Curve 2D 3

1 In the **Results** toolbar, click **More Datasets** and choose **Parameterized Curve 2D**.

2 In the **Settings** window for **Parameterized Curve 2D**, locate the **Expressions** section.

3 Select the **Only evaluate globally defined expressions** check box.

Revolution 2D 1

In the **Results** toolbar, click **More Datasets** and choose **Revolution 2D**.

Parameterized Curve 2D 3

1 In the **Model Builder** window, click **Parameterized Curve 2D 3**.

2 In the **Settings** window for **Parameterized Curve 2D**, locate the **Expressions** section.

3 In the **z** text field, type `Rfar*s`.

Revolution 2D 1

1 In the **Model Builder** window, click **Revolution 2D 1**.

2 In the **Settings** window for **Revolution 2D**, click to expand the **Revolution Layers** section.

3 In the **Start angle** text field, type `-50`.

4 In the **Revolution angle** text field, type `230`.

Grid 2D 1

1 In the **Results** toolbar, click **More Datasets** and choose **Grid>Grid 2D**.

2 In the **Settings** window for **Grid 2D**, locate the **Parameter Bounds** section.

3 Find the **First parameter** subsection. In the **Name** text field, type `r`.

4 In the **Minimum** text field, type `-1.5*Rmodel`.

5 In the **Maximum** text field, type `1.5*Rmodel`.

6 Find the **Second parameter** subsection. In the **Name** text field, type `z`.

7 In the **Maximum** text field, type `3*Rmodel`.

Mirror 2D 1

1 In the **Results** toolbar, click **More Datasets** and choose **Mirror 2D**.

2 In the **Model Builder** window, click **Results**.

3 In the **Settings** window for **Results**, locate the **Save Data in the Model** section.

4 From the **Save plot data** list, choose **On**.

Acoustic Pressure

1 In the **Results** toolbar, click **2D Plot Group**.

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

3 Locate the **Data** section. From the **Parameter value (freq (Hz))** list, choose **10000**.

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

5 Locate the **Color Legend** section. Select the **Show maximum and minimum values** check box.

6 Select the **Show units** check box.

Surface 1

1 In the **Acoustic Pressure** toolbar, click **Surface**.

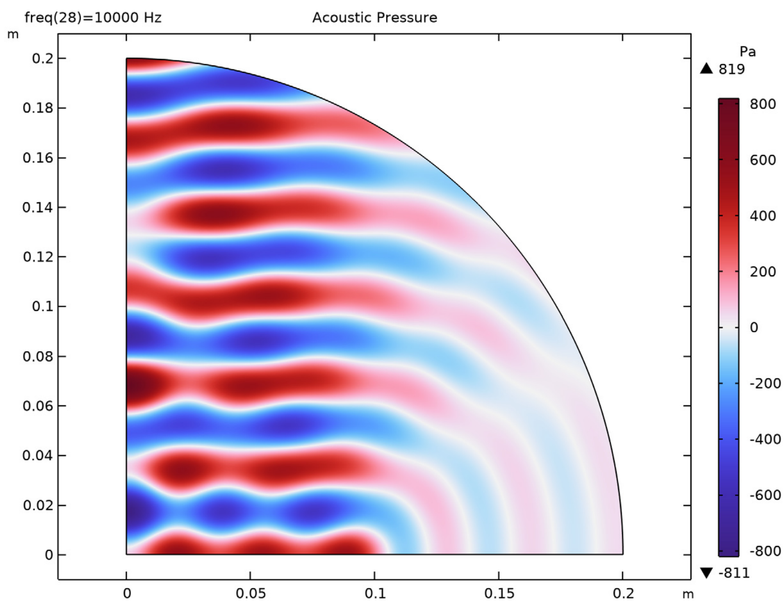
2 In the **Settings** window for **Surface**, locate the **Coloring and Style** section.

3 Click **Change Color Table**.

4 In the **Color Table** dialog box, select **Wave>Wave** in the tree.

5 Click **OK**.

6 In the **Acoustic Pressure** toolbar, click **Plot**.



On-axis Acoustic Pressure

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `On-axis Acoustic Pressure` in the **Label** text field.

3 Locate the **Data** section. From the **Parameter selection (freq)** list, choose **Last**.

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

5 Locate the **Plot Settings** section.

6 Select the **x-axis label** check box. In the associated text field, type `z/R0`.

7 Select the **y-axis label** check box. In the associated text field, type `abs(p) (Pa)`.

8 Locate the **Axis** section. Select the **x-axis log scale** check box.

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

Line Graph 1

1 In the **On-axis Acoustic Pressure** toolbar, click **Line Graph**.

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

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog box, type `1` in the **Selection** text field.

5 Click **OK**.

6 In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.

7 In the **Expression** text field, type `abs(p/p0)`.

8 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

9 In the **Expression** text field, type `z/R0`.

10 Click to expand the **Coloring and Style** section. From the **Color** list, choose **Blue**.

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

12 Click to expand the **Legends** section. Select the **Show legends** check box.

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

14 In the table, enter the following settings:

Legends
`COMSOL Model`

On-axis Acoustic Pressure

In the **Model Builder** window, click **On-axis Acoustic Pressure**.

Line Graph 2

1 In the **On-axis Acoustic Pressure** toolbar, click **Line Graph**.

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

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog box, type `1` in the **Selection** text field.

5 Click **OK**.

6 In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.

7 In the **Expression** text field, type `abs(p_axis/p0)`.

8 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

9 In the **Expression** text field, type `z/R0`.

10 Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **None**.

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

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

13 Find the **Line markers** subsection. From the **Marker** list, choose **Point**.

14 From the **Positioning** list, choose **Interpolated**.

15 In the **Number** text field, type `100`.

16 Locate the **Legends** section. Select the **Show legends** check box.

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

18 In the table, enter the following settings:

Legends
`Full Analytical`

On-axis Acoustic Pressure

In the **Model Builder** window, click **On-axis Acoustic Pressure**.

Line Graph 3

1 In the **On-axis Acoustic Pressure** toolbar, click **Line Graph**.

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

3 From the **Dataset** list, choose **Parameterized Curve 2D 2**.

4 From the **Parameter selection (freq)** list, choose **Last**.

5 Locate the **y-Axis Data** section. In the **Expression** text field, type `abs(pext(0,z)/p0)`.

6 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

7 In the **Expression** text field, type `z/R0`.

8 Locate the **Coloring and Style** section. From the **Color** list, choose **Blue**.

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

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

11 In the table, enter the following settings:

Legends
`COMSOL FE Model`

On-axis Acoustic Pressure

In the **Model Builder** window, click **On-axis Acoustic Pressure**.

Line Graph 4

1 In the **On-axis Acoustic Pressure** toolbar, click **Line Graph**.

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

3 From the **Dataset** list, choose **Parameterized Curve 2D 2**.

4 From the **Parameter selection (freq)** list, choose **Last**.

5 Locate the **y-Axis Data** section. In the **Expression** text field, type `abs(p_axis_ff/p0)`.

6 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

7 In the **Expression** text field, type `z/R0`.

8 Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **None**.

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

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

11 Find the **Line markers** subsection. From the **Marker** list, choose **Point**.

12 From the **Positioning** list, choose **Interpolated**.

13 In the **Number** text field, type `20`.

On-axis Acoustic Pressure

In the **Model Builder** window, click **On-axis Acoustic Pressure**.

Line Graph 5

1 In the **On-axis Acoustic Pressure** toolbar, click **Line Graph**.

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

3 From the **Dataset** list, choose **Parameterized Curve 2D 3**.

4 From the **Parameter selection (freq)** list, choose **Last**.

5 Locate the **y-Axis Data** section. In the **Expression** text field, type `2/sqrt(1+(2*z/R0)^2)`.

6 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

7 In the **Expression** text field, type `z/R0`.

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

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

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

11 Locate the **Legends** section. Select the **Show legends** check box.

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

13 In the table, enter the following settings:

Legends
`Asymptotes M and MM`

On-axis Acoustic Pressure

In the **Model Builder** window, click **On-axis Acoustic Pressure**.

Line Graph 6

1 In the **On-axis Acoustic Pressure** toolbar, click **Line Graph**.

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

3 From the **Dataset** list, choose **Parameterized Curve 2D 3**.

4 From the **Parameter selection (freq)** list, choose **Last**.

5 Locate the **y-Axis Data** section. In the **Expression** text field, type `1/sqrt(1+(z/R0)^2)`.

6 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

7 In the **Expression** text field, type `z/R0`.

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

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

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

On-axis Acoustic Pressure

In the **Model Builder** window, click **On-axis Acoustic Pressure**.

Line Graph 7

1 In the **On-axis Acoustic Pressure** toolbar, click **Line Graph**.

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

3 From the **Dataset** list, choose **Parameterized Curve 2D 2**.

4 From the **Parameter selection (freq)** list, choose **Last**.

5 Locate the **y-Axis Data** section. In the **Expression** text field, type `abs(i*R0/z*exp(-i*k*z))`.

6 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

7 In the **Expression** text field, type `z/R0`.

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

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

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

11 Locate the **Legends** section. Select the **Show legends** check box.

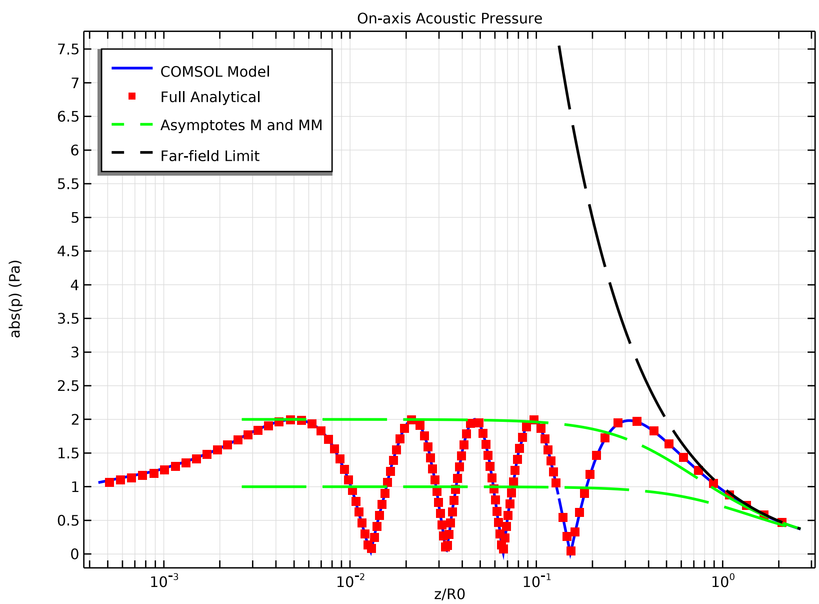
12 From the **Legends** list, choose **Manual**.

13 In the table, enter the following settings:

Legends
`Far-field Limit`

14 In the **On-axis Acoustic Pressure** toolbar, click **Plot**.

The on-axis pressure should look like the one in the figure below.



Near-field r=1.3a

1 In the **Home** toolbar, click **Add Plot Group** and choose **Polar Plot Group**.

2 In the **Settings** window for **Polar Plot Group**, type `Near-field r=1.3a` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Parameterized Curve 2D 1**.

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

5 In the **Parameter values (freq (Hz))** list, select **10000**.

6 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.

7 In the **Title** text area, type `Near-field SPL at f=eval(freq) Hz`.

8 Locate the **Axis** section. Select the **Symmetric angle range** check box.

9 From the **Zero angle** list, choose **Up**.

10 From the **Rotation direction** list, choose **Clockwise**.

Line Graph 1

1 In the **Near-field r=1.3a** toolbar, click **Line Graph**.

2 In the **Settings** window for **Line Graph**, locate the **r-Axis Data** section.

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

4 Locate the θ **Angle Data** section. From the **Parameter** list, choose **Expression**.

5 In the **Expression** text field, type `theta`.

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

Near-field r=1.3a

In the **Model Builder** window, click **Near-field r=1.3a**.

Line Graph 2

1 In the **Near-field r=1.3a** toolbar, click **Line Graph**.

2 In the **Settings** window for **Line Graph**, locate the **r-Axis Data** section.

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

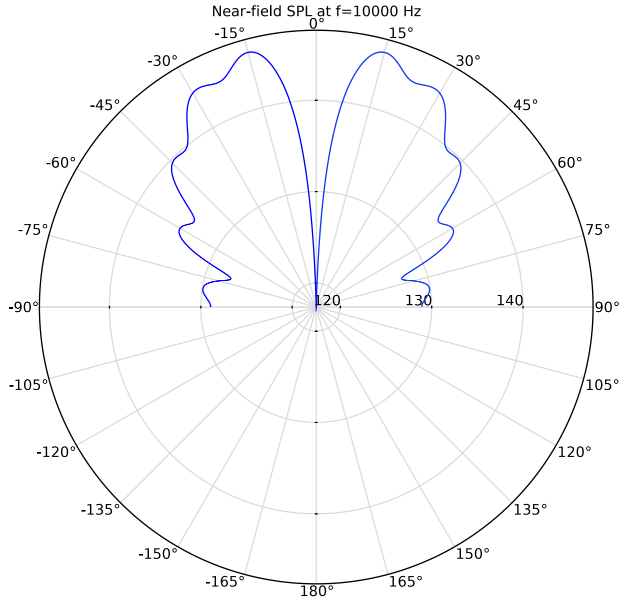
4 Locate the θ **Angle Data** section. From the **Parameter** list, choose **Expression**.

5 In the **Expression** text field, type `-theta`.

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

7 Click to expand the **Coloring and Style** section. From the **Color** list, choose **Blue**.

8 In the **Near-field r=1.3a** toolbar, click **Plot**.



Far-field r=Rfar

1 In the **Home** toolbar, click **Add Plot Group** and choose **Polar Plot Group**.

2 In the **Settings** window for **Polar Plot Group**, type `Far-field r=Rfar` in the **Label** text field.

3 Locate the **Data** section. From the **Parameter selection (freq)** list, choose **From list**.

4 In the **Parameter values (freq (Hz))** list, select **10000**.

5 Locate the **Title** section. From the **Title type** list, choose **Manual**.

6 In the **Title** text area, type `Far-field SPL at f=eval(freq) Hz`.

7 Locate the **Axis** section. Select the **Symmetric angle range** check box.

8 From the **Zero angle** list, choose **Up**.

9 From the **Rotation direction** list, choose **Clockwise**.

Radiation Pattern 1

1 In the **Far-field r=Rfar** toolbar, click **More Plots** and choose **Radiation Pattern**.

2 In the **Settings** window for **Radiation Pattern**, locate the **Evaluation** section.

3 Find the **Angles** subsection. In the **Number of angles** text field, type `180`.

4 From the **Restriction** list, choose **Manual**.

5 In the ϕ **start** text field, type `-90`.

6 In the ϕ **range** text field, type `180`.

7 Find the **Evaluation distance** subsection. In the **Radius** text field, type `Rfar`.

8 In the **Far-field r=Rfar** toolbar, click **Plot**.

Far-field r=Rfar

In the **Model Builder** window, click **Far-field r=Rfar**.

Radiation Pattern 2

1 In the **Far-field r=Rfar** toolbar, click **More Plots** and choose **Radiation Pattern**.

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

3 In the **Expression** text field, type `10*log10(0.5*p_ana*conj(p_ana)/(20e-6)^2)`.

4 Locate the **Evaluation** section. Find the **Angles** subsection. In the **Number of angles** text field, type `180`.

5 From the **Restriction** list, choose **Manual**.

6 In the ϕ **start** text field, type `-90`.

7 In the ϕ **range** text field, type `180`.

8 Find the **Evaluation distance** subsection. In the **Radius** text field, type `Rfar`.

9 Click to expand the **Legends** section. Select the **Show legends** check box.

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

11 In the table, enter the following settings:

Legends
`Analytical (far-field)`

12 Click to expand the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **None**.

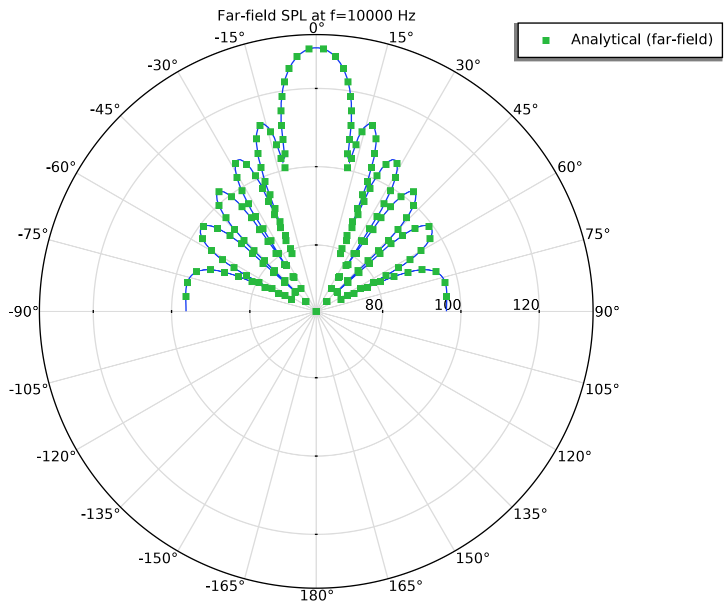
13 Find the **Line markers** subsection. From the **Marker** list, choose **Point**.

14 From the **Positioning** list, choose **Interpolated**.

15 In the **Number** text field, type `180`.

16 In the **Far-field r=Rfar** toolbar, click **Plot**.

The far-field radiation pattern at f=10,000 Hz should look like the one in the figure below.



Beamwidth Polar

1 In the **Home** toolbar, click **Add Plot Group** and choose **Polar Plot Group**.

2 In the **Settings** window for **Polar Plot Group**, type `Beamwidth Polar` in the **Label** text field.

3 Locate the **Axis** section. Select the **Symmetric angle range** check box.

4 From the **Zero angle** list, choose **Up**.

5 From the **Rotation direction** list, choose **Clockwise**.

Radiation Pattern 1

1 In the **Beamwidth Polar** toolbar, click **More Plots** and choose **Radiation Pattern**.

2 In the **Settings** window for **Radiation Pattern**, locate the **Evaluation** section.

3 Find the **Angles** subsection. In the **Number of angles** text field, type `90`.

4 From the **Restriction** list, choose **Manual**.

5 In the ϕ **start** text field, type `-90`.

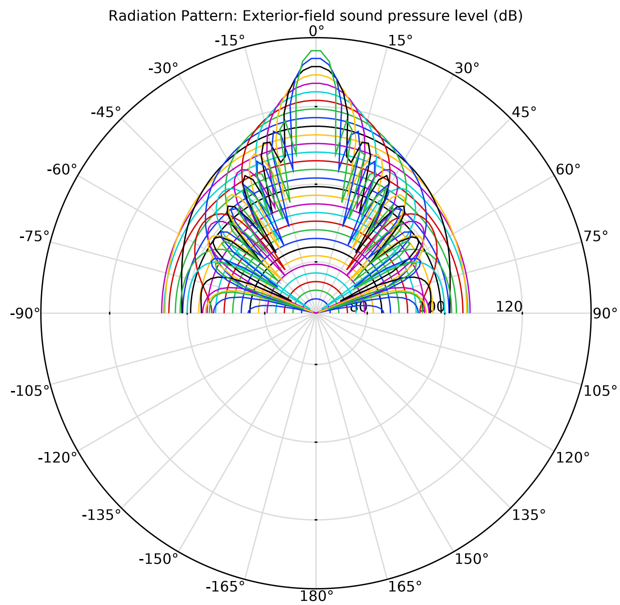
6 In the ϕ **range** text field, type `180`.

7 From the **Compute beamwidth** list, choose **On**.

8 In the **Level down** text field, type `3`.

9 Find the **Evaluation distance** subsection. In the **Radius** text field, type `Rfar`.

10 In the **Beamwidth Polar** toolbar, click **Plot**.



Beamwidth

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

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

3 Locate the **Data** section. From the **Dataset** list, choose **None**.

4 Locate the **Title** section. From the **Title type** list, choose **Label**.

5 Locate the **Plot Settings** section.

6 Select the **x-axis label** check box. In the associated text field, type `f (Hz)`.

7 Select the **y-axis label** check box. In the associated text field, type `Beamwidth (deg)`.

Table Graph 1

1 In the **Beamwidth** toolbar, click **Table Graph**.

2 In the **Settings** window for **Table Graph**, click to expand the **Legends** section.

3 Select the **Show legends** check box.

Beamwidth

In the **Beamwidth** toolbar, click **Global**.

Global 1

1 In the **Settings** window for **Global**, locate the **Data** section.

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

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

Expression	Unit	Description
`2*asin(1.616/ka)/pi*180`	`rad`	`Beamwidth (-3 dB), analytical`
`2*asin(0.610*2*pi/ka)/pi*180`	`rad`	`Null-to-null beamwidth, analytical`

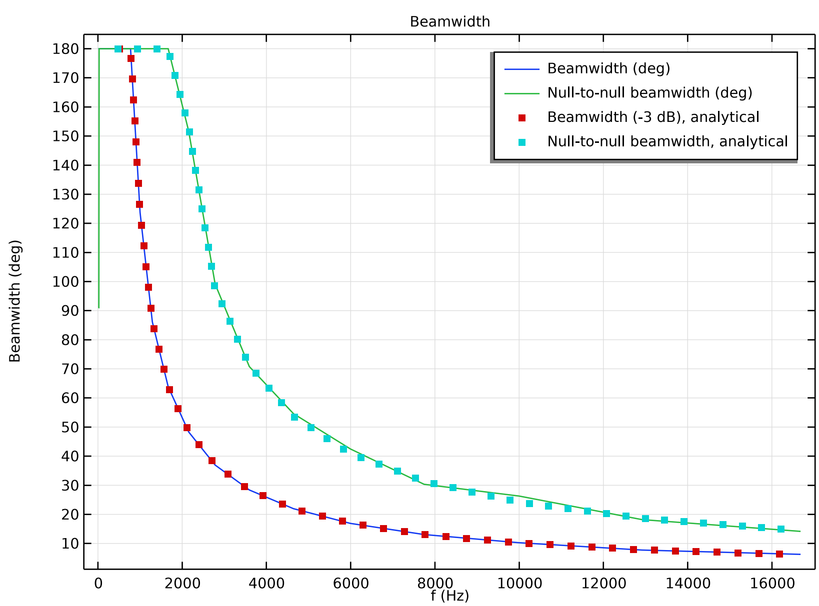
4 Click to expand the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **None**.

5 Find the **Line markers** subsection. From the **Marker** list, choose **Point**.

6 From the **Positioning** list, choose **Interpolated**.

7 In the **Number** text field, type 50.

8 In the **Beamwidth** toolbar, click **Plot**.



Radiated Power

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

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

3 Locate the **Title** section. From the **Title type** list, choose **Label**.

4 Locate the **Plot Settings** section.

5 Select the **x-axis label** check box. In the associated text field, type `f (Hz)`.

6 Select the **y-axis label** check box. In the associated text field, type `Power (W)`.

7 Locate the **Axis** section. Select the **x-axis log scale** check box.

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

Global 1

1 In the **Radiated Power** toolbar, click **Global**.

2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.

3 In the table, enter the following settings:

Expression	Unit	Description
W	W	COMSOL Model

4 Locate the **Coloring and Style** section. From the **Width** list, choose **2**.

Radiated Power

In the **Radiated Power** toolbar, click **Global**.

Global 2

1 In the **Settings** window for **Global**, locate the **y-Axis Data** section.

2 In the table, enter the following settings:

Expression	Unit	Description
W_ana	W	Radiated power (analytical)

3 Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **None**.

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

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

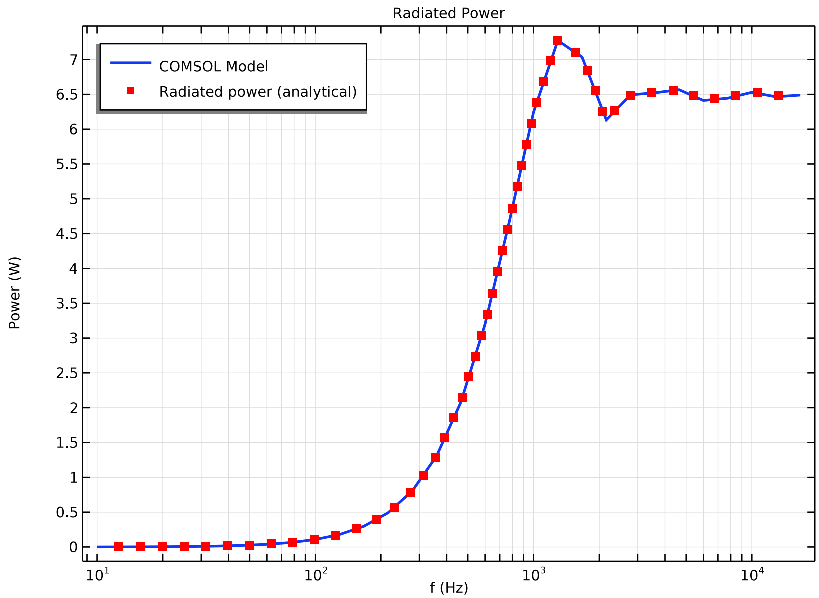
6 Find the **Line markers** subsection. From the **Marker** list, choose **Point**.

7 From the **Positioning** list, choose **Interpolated**.

8 In the **Number** text field, type `50`.

9 In the **Radiated Power** toolbar, click **Plot**.

The total radiated power should look like the one in the figure below.



Exterior Field

1 In the **Home** toolbar, click **Add Plot Group** and choose **2D Plot Group**.

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

3 Locate the **Data** section. From the **Dataset** list, choose **Grid 2D 1**.

4 From the **Parameter value (freq (Hz))** list, choose **5994.8**.

5 Locate the **Title** section. From the **Title type** list, choose **Label**.

6 Locate the **Color Legend** section. Select the **Show units** check box.

Surface 1

1 In the **Exterior Field** toolbar, click **Surface**.

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

3 From the **Dataset** list, choose **Mirror 2D 1**.

4 From the **Parameter value (freq (Hz))** list, choose **5994.8**.

5 Locate the **Coloring and Style** section. Click **Change Color Table**.

6 In the **Color Table** dialog box, select **Wave>Wave** in the tree.

7 Click **OK**.

Height Expression 1

1 In the **Exterior Field** toolbar, click **Height Expression**.

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

3 Select the **Scale factor** check box. In the associated text field, type `1.E-4`.

4 In the **Offset** text field, type `0.15`.

Exterior Field

In the **Model Builder** window, under **Results** click **Exterior Field**.

Surface 2

1 In the **Exterior Field** toolbar, click **Surface**.

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

3 In the **Expression** text field, type `pext(r,z)`.

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

Filter 1

In the **Exterior Field** toolbar, click **Filter**.

It is necessary to use a filter here for the computation of the Kirchhoff-Helmholtz integral (Exterior Field). The kernel is not numerically well defined near the source boundaries.

1 In the **Settings** window for **Filter**, locate the **Element Selection** section.

2 In the **Logical expression for inclusion** text field, type `sqrt(z^2+r^2)>1.01*Rmodel`.

Surface 2

In the **Model Builder** window, click **Surface 2**.

Height Expression 1

1 In the **Exterior Field** toolbar, click **Height Expression**.

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

3 In the **Offset** text field, type `0.15`.

Exterior Field

In the **Model Builder** window, under **Results** click **Exterior Field**.

Contour 1

1 In the **Exterior Field** toolbar, click **Contour**.

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

3 From the **Dataset** list, choose **Mirror 2D 1**.

4 From the **Parameter value (freq (Hz))** list, choose **5994.8**.

5 Locate the **Coloring and Style** section. Click **Change Color Table**.

6 In the **Color Table** dialog box, select **Wave>Wave** in the tree.

7 Click **OK**.

8 In the **Settings** window for **Contour**, locate the **Coloring and Style** section.

9 Clear the **Color legend** check box.

Exterior Field

In the **Model Builder** window, click **Exterior Field**.

Contour 2

1 In the **Exterior Field** toolbar, click **Contour**.

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

3 In the **Expression** text field, type `pext(r,z)`.

4 Locate the **Coloring and Style** section. Clear the **Color legend** check box.

5 Click to expand the **Inherit Style** section. From the **Plot** list, choose **Contour 1**.

Filter 1

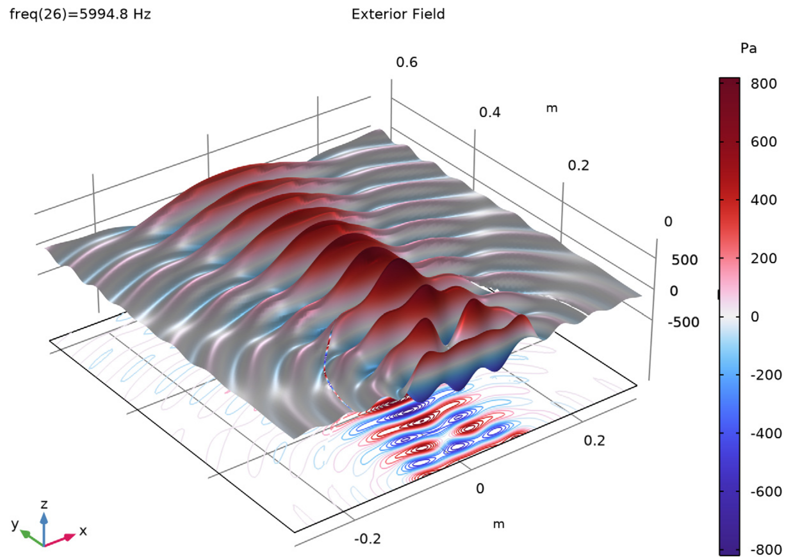
1 In the **Exterior Field** toolbar, click **Filter**.

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

3 In the **Logical expression for inclusion** text field, type `sqrt(z^2+r^2)>1.01*Rmodel`.

4 In the **Exterior Field** toolbar, click **Plot**.

The exterior field should look like the one in the figure below.



Thumbnail

1 In the **Home** toolbar, click **Add Plot Group** and choose **3D Plot Group**.

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

3 Locate the **Color Legend** section. Select the **Show units** check box.

Surface 1

1 In the **Thumbnail** toolbar, click **Surface**.

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

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

4 Locate the **Coloring and Style** section. Click **Change Color Table**.

5 In the **Color Table** dialog box, select **Rainbow>Rainbow** in the tree.

6 Click **OK**.

7 In the **Settings** window for **Surface**, locate the **Coloring and Style** section.

8 From the **Scale** list, choose **Linear**.

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