Open Pipe

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Introduction

In this tutorial model, a vibrating piston is mounted inside one end of a cylindrical pipe, while the other end of the pipe opens into an infinite domain. The problem is solved using two different approaches to illustrate their strengths and weaknesses. In the first case, an impedance boundary condition modeling radiation losses into an infinite domain is specified on the pipe end while the acoustics in the domain is not solved explicitly. This is consequently a fast approach. In the second case, a perfectly matched layer condition is applied on the domain. This condition offers a consistent and physically sound method for modeling infinite domains using finite-sized regions. Thus, the domain acoustics is explicitly solved for, but only in a region close to the pipe outlet.

The model considers two different types of pipes: a flanged and an unflanged. In both cases, the impedance-based model is compared with the model using the perfectly matched layer condition.

Model Definition

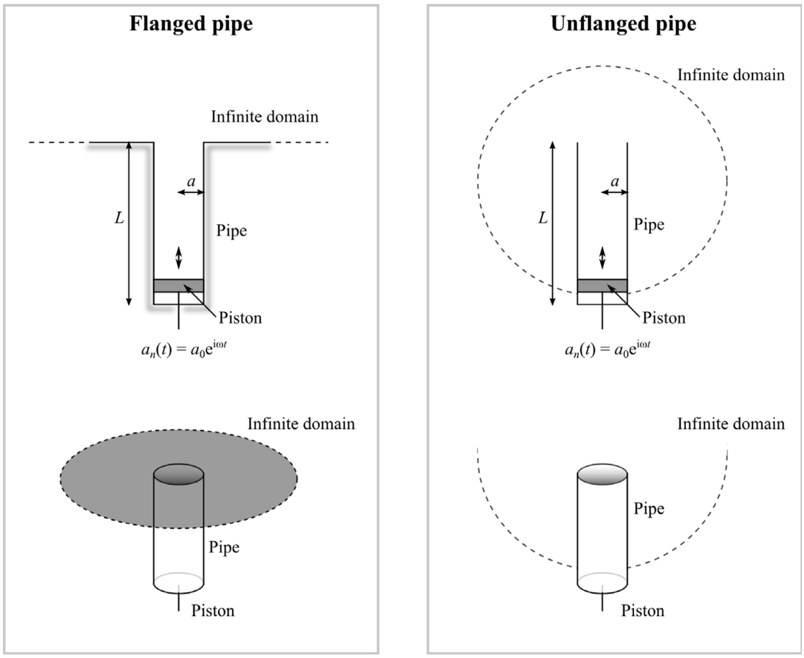


Figure 1: Sketch of the two pipe geometries considered in this model: the flanged pipe (left) and the unflanged pipe (right).

We consider the acoustics of an open pipe with a harmonically oscillating piston mounted in one end. Figure 1 shows the geometry for the two cases considered: the flanged pipe (left) and an unflanged pipe (right). In both cases, the pipe opens into an unbounded domain, and the piston is mounted at the bottom end of the pipe.

The pipe has length L = 1.5 m and radius a = 0.25 m. The piston provides a harmonically oscillating acceleration $a_n(t) = a_0 e^{i\omega t}$ in the axial direction at the end of the pipe, where $\omega = 2\pi f$ [rad/s] is the angular frequency corresponding to the frequency f [Hz]. The model sweeps in the frequency f, from 10 Hz to 1000 Hz. The acoustic medium is air with the density 1.25 kg m^{-3} and the speed of sound c = 343 m/s.

The axial symmetry of both the physics and the geometry allows us to exploit the 2D axisymmetry interface.

MODELING THE UNBOUNDED DOMAIN

For either geometry, you can model the infinite domain in two separate ways. In the first case, you apply an impedance boundary condition on the pipe outlet, and otherwise ignore the external domain. The impedance is an analytical, geometry-specific model, so the choice of impedance model specifies the geometry of the domain (that is, whether the pipe is flanged or not). This is a computationally efficient method, because you do not need to explicitly model the external domain. However, the analytical expression for the impedance assumes that the incident waves is strictly plane on the outlet. This is always true for low frequencies, but for higher frequencies the geometry can also support nonplane waves. Moreover, the far field of the sound radiation will in this case start to exhibit directivity (a far-field beam pattern with lobes), which will introduce additional deviations for the simple impedance approach. The cutoff frequency is given by Ref. 1

$$f_{\mathrm{c}} = \frac{\alpha\frac{c}{a}}{2\pi}$$

where $\alpha = 3.832$ is the first root of the Bessel function of the first kind of order 1 and the rest of the parameters are given above. The exact value is $f_{\mathrm{c}} = 836.76$ Hz. Above this frequency, you cannot expect the impedance-based model to provide the exact result.

In the second case, you explicitly model the surrounding domain. To do so, use a perfectly matched layer (PML) condition to model the unboundedness of the domain and therefore only model a finite region. The PML condition is an artificial absorbing layer, which can be used to truncate the domain while still simulating open boundaries. Compared to the impedance-based model, this approach is more computationally heavy because it also solves for the acoustics in the domain, albeit a truncated one. However, because the domain is modeled explicitly, this approach automatically supports frequencies above the cutoff frequency f_{c} where nonplane waves can exist.

GOVERNING EQUATION

Being a time-harmonic problem, this model uses the frequency-domain Helmholtz equation for the sound pressure amplitude p

$$\nabla \cdot \left[-\frac{1}{\rho}\nabla p\right] - \frac{\omega^2}{\rho c^2}p = 0 \qquad (1)$$

where ρ is the density of the air. The full pressure is given by $p(t) = p e^{i\omega t}$. Comparing to the equation display in the COMSOL Desktop window, Equation 1 does not contain the dipole source $\mathbf{q}$, because no such dipole sources are present in the domain.

BOUNDARY CONDITIONS

As already touched upon, you can use two different types of boundary conditions to model the unbounded domain in this problem: an impedance condition imposed on the pipe outlet, or an explicit model of the surrounding domain with a perfectly matched layer to simulate the open boundaries. The former case requires the addition of a separate equation on the boundary as detailed below, while the latter does not.

An impedance boundary condition stipulates a relationship between the pressure p and the boundary-normal velocity v at the pipe outlet. It is defined as $Z_\mathrm{i} = p/v$ and is typically frequency dependent. The impedance boundary conditions are invoked by imposing the following equation on the open end of the pipe

$$-\mathbf{n}\cdot\left(\frac{1}{\rho}\nabla p\right) = \frac{i\omega p}{Z_\mathrm{i}},$$

where $\mathbf{n}$ is the outward pointing normal vector to the boundary. A complex value of the impedance indicates losses and associated phase-shift between the pressure and the boundary-normal velocity.

In addition to handling the unbounded domain, the model also includes conditions to model the oscillating piston as well as the hard side walls of the pipe and the flange (the latter where applicable). The oscillating piston is modeled by imposing a harmonically oscillating acceleration at the pipe inlet

$$\mathbf{n}\cdot\left(\frac{1}{\rho}\nabla p\right) = a_0,$$

where a_0 is the amplitude of the harmonically oscillating acceleration.

For the flanged pipe, the hard walls of the pipe and flange are given by applying the following equation on the appropriate boundaries

$$\mathbf{n}\cdot\left(\frac{1}{\rho}\nabla p\right) = 0. \qquad (2)$$

The unflanged pipe furthermore has places with air on both sides of the pipe wall. On these wall segments, the condition above applies to the fluid on both sides,

$$\mathbf{n}\cdot\left(\frac{1}{\rho}\nabla p\right)_1 = 0$$

$$\mathbf{n}\cdot\left(\frac{1}{\rho}\nabla p\right)_2 = 0$$

with the fluid on the two sides of the pipe wall denoted by subscripts ‘1’ and ‘2’, respectively. Wall segments with air on only one side are modeled using Equation 2.

Results and Discussion

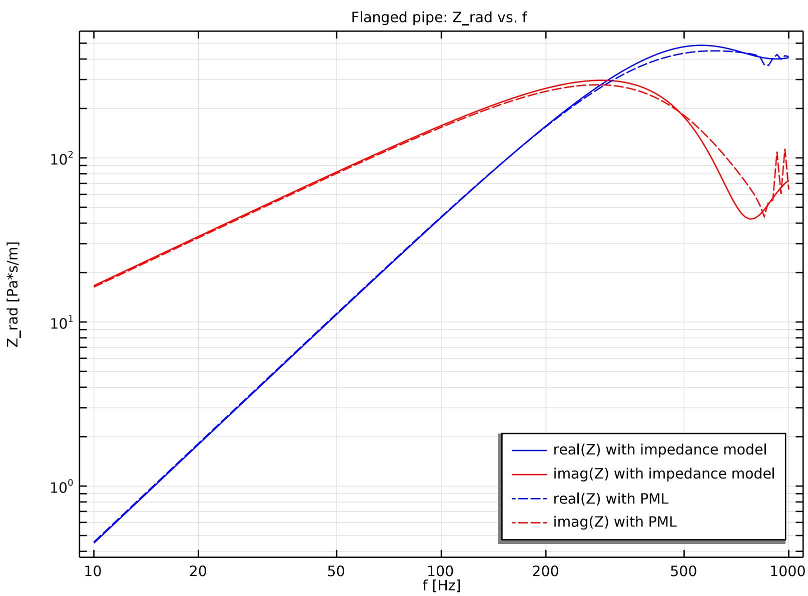


Figure 2: Impedance Z_i as a function of driving frequency f for the flanged pipe. For the PML model, the implied impedance is derived according to Equation 3.

FLANGED PIPE

First consider the results from the flanged pipe. We are ultimately interested in comparing the pipe outlet pressure between the two modeling approaches (impedance or PMLs), but an important factor in this regard is to investigate the radiated losses at the pipe outlet. For the impedance-based model, these are exactly what the impedance Z_i expresses. To compare this to the model with PMLs, compute an implied impedance on the pipe outlet by taking the ratio of the boundary-average pressure $\langle p \rangle$ to the boundary-average of the boundary-normal velocity $\langle v \rangle$. Thus, since the pipe outlet boundary is circular with radius a, the implied impedance for the PML model is

$$Z_i = \frac{\langle p\rangle}{\langle v\rangle} = \frac{\frac{1}{\pi a^2}2\pi\int_0^a rp \ \ dr}{\frac{1}{\pi a^2}2\pi\int_0^a rv \ \ dr} = \frac{\int_0^a rp \ \ dr}{\int_0^a rv \ \ dr}. \tag{3}$$

Figure 2 shows the result of this comparison. As expected, there is good comparison between the two modeling approaches until the cutoff frequency of f_c = 836.76 Hz. Above this, the nonplane waves supported by the geometry are observed to become increasingly influential as the impedance-based model (solid lines) begin to deviate.

Several impedance models have been derived as analytical approximations valid only for limited regimes of the relative wave number $k{\cdot}a$. To illustrate this, Figure 3 repeats the plot in Figure 2 but shown as a function of $k{\cdot}a$ rather than f.

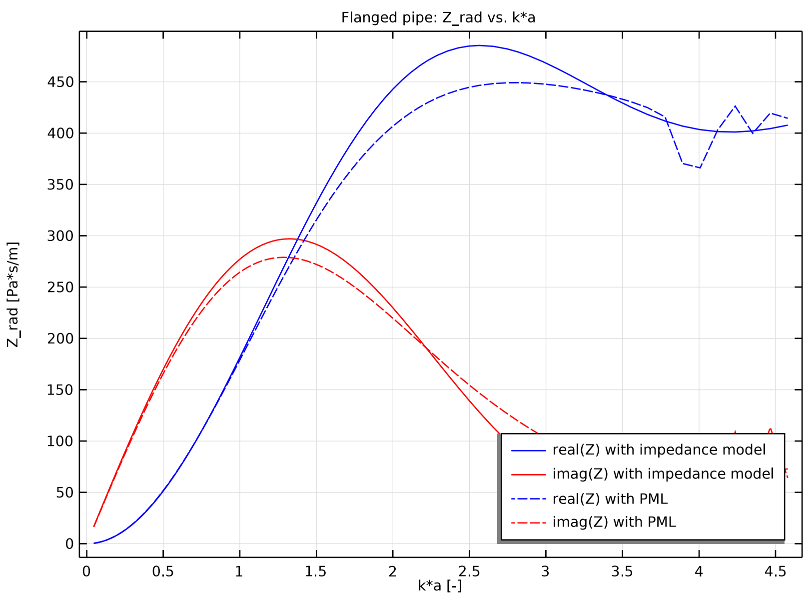


Figure 3: Impedance Z_i as a function of relative wave number $k{\cdot}a$ for the flanged pipe. For the PML model, the implied impedance is derived according to Equation 3.

Finally, compare in Figure 4 the pressure at the centerline of the pipe outlet from the two models. There is good agreement across all frequencies even though the impedances exhibit some variations at higher frequencies (see Figure 2).

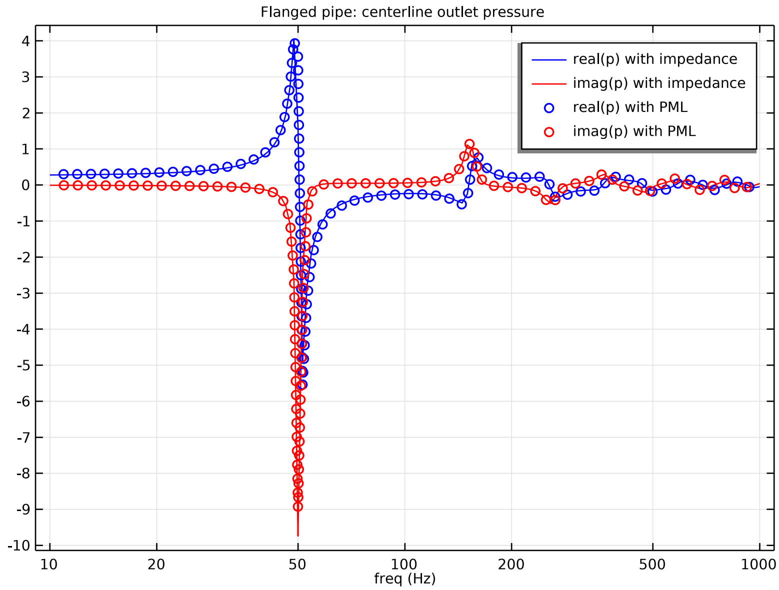


Figure 4: Pipe outlet pressure p for the flanged pipe for both impedance and PML models. In spite of noticeable variations for the impedances at higher frequencies (Figure 2), the predicted pressure from the two models is in general in good agreement across all frequencies.

UNFLANGED PIPE

Then repeat the analysis for an unflanged pipe. In this case, the impedance model is an approximate analytical solution valid only for small values of $k{\cdot}a$. Figure 5–Figure 7 show the results of this analysis; these are analogous to the pipe results above for the flanged pipe and therefore warrant only short mention.

Figure 5 illustrates that the analytical and implied impedances are comparable across the entire frequency range. However, for $k{\cdot}a$ greater than about 2, the analytical impedance deviates quite significantly; see Figure 6. This is not quite as expected since the impedance model should apply for $k{\cdot}a < 3.83$; however, this could be due to the model itself being an approximation, not an exact analytical result even for low $k{\cdot}a$. Nonetheless, Figure 7 illustrates that the predicted centerline outlet pressure from either the impedance-based model or the PML model are in fair agreement across the entire range of probed frequencies.

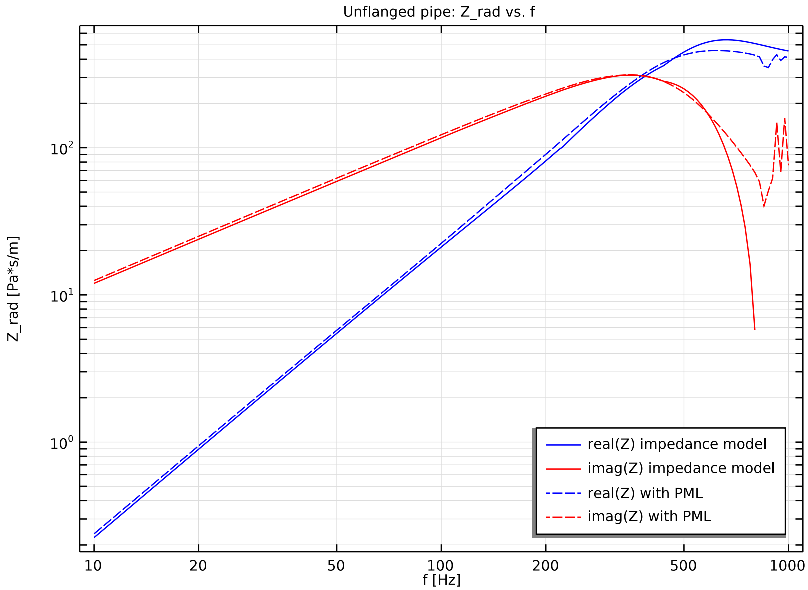


Figure 5: Impedance Z_i as a function of driving frequency f for the unflanged pipe. For the PML model, the implied impedance is derived according to Equation 3.

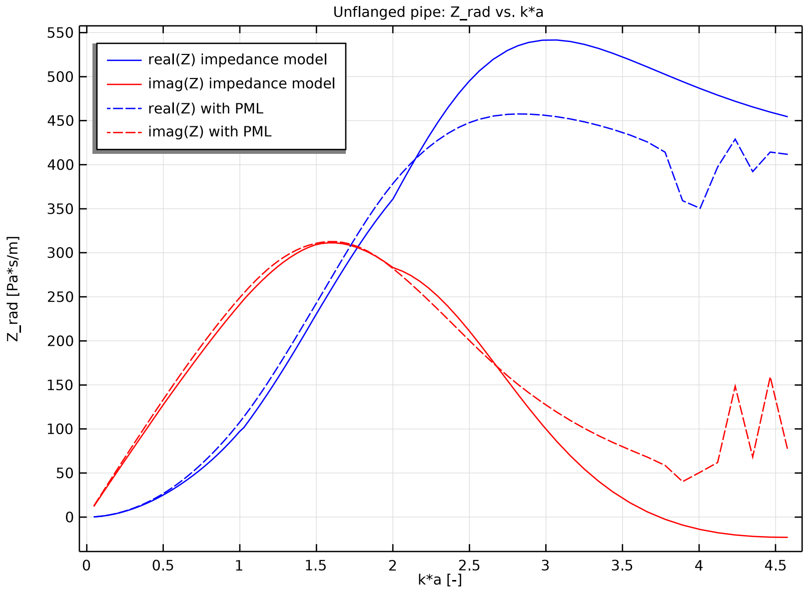


Figure 6: Impedance Z_i *as a function of driving relative wave number* $k{\cdot}a$ *for the unflanged pipe. For the PML model, the implied impedance is derived according to* Equation 3.

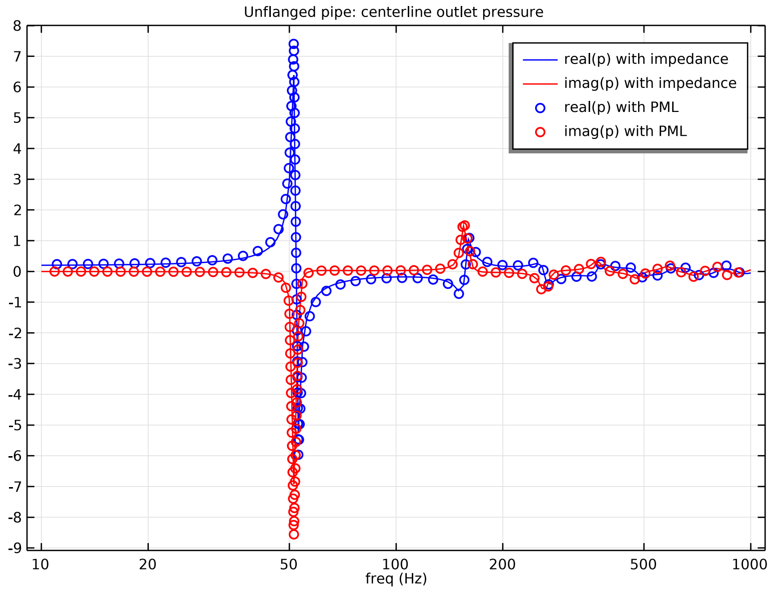


Figure 7: Pressure p at the centerline of the pipe outlet for the unflanged pipe.

Notes About the COMSOL Implementation

In anticipation of using a frequency sweep covering several decades, define the frequency limits `fmin` and `fmax` as exponents without units and set the frequency range to $10^{\mathtt{fmin}}-10^{\mathtt{fmax}}$.

Reference

1. D.T. Blackstock, *Fundamentals of physical acoustics*, John Wiley & Sons, 2000.

Application Library path: `Acoustics_Module/Verification_Examples/open_pipe`

Modeling Instructions

You start by modeling a flanged pipe. You will be comparing the two different approaches for solving the problem, so start by immediately adding the physics option twice.

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 **Add**.

5 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 `open_pipe_parameters.txt`.

GEOMETRY 1

First model the pipe.

Rectangle 1 (r1)

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

2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

3 In the **Width** text field, type `a`.

4 In the **Height** text field, type `L`.

5 Locate the **Position** section. In the **z** text field, type `-L`.

Now model the surroundings. Only use a quarter circle to model the flange on the pipe.

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 `6*a`.

4 In the **Sector angle** text field, type 90.

Add an external layer to the circle. You will later apply the Perfectly Matched Layer (PML) condition in this layer.

5 Click to expand the **Layers** section. In the table, enter the following settings:

Layer name	Thickness (m)
Layer 1	2*a

6 Click **Build All Objects**.

7 Click the **Zoom Extents** button in the **Graphics** toolbar.

In pressure acoustics you only need to specify the density and speed of sound. When these parameters are known, this is most easily done by adding a blank material and providing the parameter values. Otherwise, add a built-in material. In this case you add the parameter values for air.

MATERIALS

Material 1 (mat1)

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **Blank Material**.

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

3 In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Density	rho	rho_air	kg/m³	Basic
Speed of sound	c	c_air	m/s	Basic

COMPONENT 1 - FLANGED PIPE RADIATION

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

2 In the **Settings** window for **Component**, type Component 1 - Flanged pipe radiation in the **Label** text field.

Set up the model of the flanged pipe using an impedance boundary condition.

PRESSURE ACOUSTICS, FREQUENCY DOMAIN - IMPEDANCE MODEL

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

2 In the **Settings** window for **Pressure Acoustics, Frequency Domain**, type `Pressure Acoustics, Frequency Domain - impedance model` in the **Label** text field.

3 Select Domain 1 only.

Normal Acceleration 1

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

2 Select Boundary 2 only.

3 In the **Settings** window for **Normal Acceleration**, locate the **Normal Acceleration** section.

4 In the a_n text field, type `a0`.

Impedance 1

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

2 Select Boundary 4 only.

3 In the **Settings** window for **Impedance**, locate the **Impedance** section.

4 From the **Impedance model** list, choose **Waveguide end impedance**.

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

Now set up the model of the flanged pipe using a perfectly matched layer condition.

PRESSURE ACOUSTICS, FREQUENCY DOMAIN 2 - PERFECTLY MATCHED LAYERS

1 In the **Model Builder** window, under **Component 1 - Flanged pipe radiation (comp1)** click **Pressure Acoustics, Frequency Domain 2 (acpr2)**.

2 In the **Settings** window for **Pressure Acoustics, Frequency Domain**, type `Pressure Acoustics, Frequency Domain 2 - perfectly matched layers` in the **Label** text field.

Set up the perfectly matched layer. Also set up a nonlocal integration coupling on the pipe outlet; this operator will be used for postprocessing.

DEFINITIONS

Perfectly Matched Layer 1 (pml1)

1 In the **Definitions** toolbar, click **Perfectly Matched Layer**.

2 Select Domain 3 only.

3 In the **Settings** window for **Perfectly Matched Layer**, locate the **Scaling** section.

4 From the **Coordinate stretching type** list, choose **Rational**.

5 From the **Physics** list, choose **Pressure Acoustics, Frequency Domain 2 - perfectly matched layers (acpr2)**.

6 In the **PML scaling factor** text field, type `0.5`.

7 In the **PML scaling curvature parameter** text field, type `5`.

DEFINITIONS

Integration 1 (intop1)

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

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

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

4 Select Boundary 4 only.

PRESSURE ACOUSTICS, FREQUENCY DOMAIN 2 - PERFECTLY MATCHED LAYERS (ACPR2)

Normal Acceleration 1

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

2 Select Boundary 2 only.

3 In the **Settings** window for **Normal Acceleration**, locate the **Normal Acceleration** section.

4 In the a_n text field, type `a0`.

MESH 1

In this model, the mesh is set up manually. Proceed by directly adding the desired mesh component. In general, 5 to 6 second-order elements per wavelength are needed to resolve the waves. For more details, see *Meshing (Resolving the Waves)* in the *Acoustics Module User's Guide*. Here, we use 6 elements per wavelength.

Free Triangular 1

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

Size

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

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

3 Click the **Custom** button.

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

5 In the **Minimum element size** text field, type `6.0E-4`.

Free Triangular 1

1 In the **Model Builder** window, click **Free Triangular 1**.

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

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

4 Select Domains 1 and 2 only.

Size 1

1 Right-click **Free Triangular 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 **Point**.

4 Select Point 6 only.

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

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

7 Select the **Maximum element size** check box. In the associated text field, type `hmax/15`.

MESH 1

Free Triangular 1

In the **Model Builder** window, collapse the **Component 1 - Flanged pipe radiation (comp1)>Mesh 1>Free Triangular 1** node.

Mapped 1

In the **Mesh** toolbar, click **Mapped**.

Distribution 1

1 Right-click **Mapped 1** and choose **Distribution**.

2 Select Boundary 8 only.

3 In the **Settings** window for **Distribution**, locate the **Distribution** section.

4 In the **Number of elements** text field, type `14`.

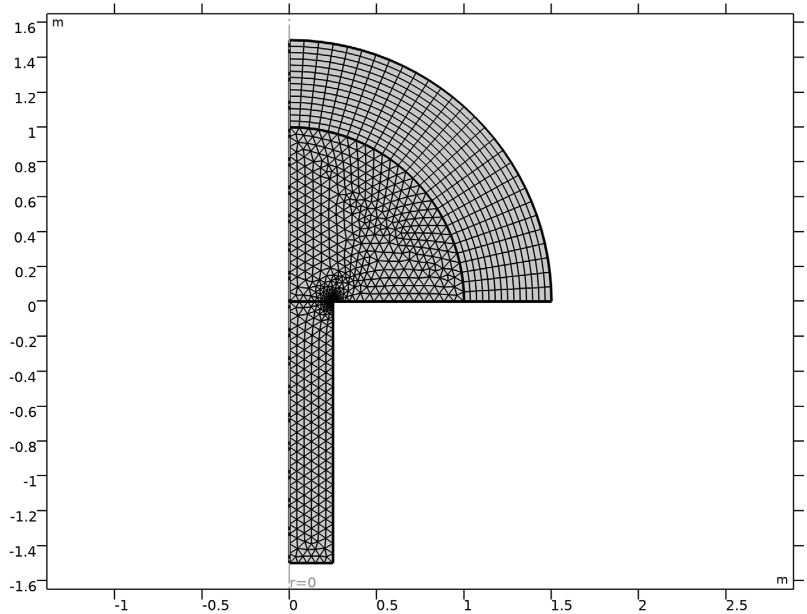
MESH 1

Mapped 1

1 In the **Model Builder** window, collapse the **Component 1 - Flanged pipe radiation (comp1)>Mesh 1>Mapped 1** node.

2 In the **Model Builder** window, right-click **Mesh 1** and choose **Build All**.

3 Click the **Zoom Extents** button in the **Graphics** toolbar.



Mesh used to simulate the flanged pipe. The layer external to the quarter hemisphere is used for the perfectly matched layer.

Next add two separate studies, one for each model (impedance-based model and model with perfectly matched layers).

ADD STUDY

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

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

3 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies>Frequency Domain**.

4 Click **Add Study** in the window toolbar.

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

6 Click **Add Study** in the window toolbar.

7 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 2

Step 1: Frequency Domain

Set up the study for the impedance-based model. This includes specifying solution frequencies and making sure that only the impedance-based model is solved. As default, the software will include both models, so you disable the model with perfectly matched layers.

STUDY 1 - FLANGED PIPE WITH IMPEDANCE BC

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

2 In the **Settings** window for **Study**, type `Study 1 - Flanged pipe with impedance BC` in the **Label** text field.

Step 1: Frequency Domain

1 In the **Model Builder** window, under **Study 1 - Flanged pipe with impedance BC** 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 **ISO preferred frequencies** from the **Entry method** list.

5 In the **Start frequency** text field, type `fmin`.

6 In the **Stop frequency** text field, type `fmax`.

7 From the **Interval** list, choose **1/24 octave**.

8 Click **Replace**.

Here you disable the model with perfectly matched layers.

9 In the **Settings** window for **Frequency Domain**, locate the **Physics and Variables Selection** section.

10 In the table, clear the **Solve for** check box for **Pressure Acoustics, Frequency Domain 2 - perfectly matched layers (acpr2)**.

Set up the study for the model with perfectly matched layers similar to the other study above.

STUDY 2 - FLANGED PIPE WITH PML

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

2 In the **Settings** window for **Study**, type `Study 2 - Flanged pipe with PML` in the **Label** text field.

3 Locate the **Study Settings** section. Clear the **Generate default plots** check box.

Step 1: Frequency Domain

1 In the **Model Builder** window, under **Study 2 - Flanged pipe with PML** 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 **ISO preferred frequencies** from the **Entry method** list.
5 In the **Start frequency** text field, type `fmin`.
6 In the **Stop frequency** text field, type `fmax`.
7 From the **Interval** list, choose **1/24 octave**.
8 Click **Replace**.

   Disable the impedance-based model.

9 In the **Settings** window for **Frequency Domain**, locate the **Physics and Variables Selection** section.
10 In the table, clear the **Solve for** check box for **Pressure Acoustics, Frequency Domain - impedance model (acpr)**.

STUDY 1 - FLANGED PIPE WITH IMPEDANCE BC

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

STUDY 2 - FLANGED PIPE WITH PML

Click **Compute**.

Compare the pipe outlet impedance between the impedance-based model and the model with perfectly matched layers.

RESULTS

Create the plot in Figure 2.

Flanged pipe: Z_rad vs. f

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.
2 In the **Settings** window for **1D Plot Group**, type `Flanged pipe: Z_rad vs. f` in the **Label** text field.
3 Locate the **Data** section. From the **Dataset** list, choose **None**.
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 `f [Hz]`.

7 Select the **y-axis label** check box. In the associated text field, type `Z_rad [Pa*s/m]`.

Point Graph 1

1 Right-click **Flanged pipe: Z_rad vs. f** and choose **Point Graph**.

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

3 From the **Dataset** list, choose **Study 1 - Flanged pipe with impedance BC/Solution 1 (sol1)**.

4 Select Point 2 only.

5 Locate the **y-Axis Data** section. In the **Expression** text field, type `real(acpr.imp1.Zn)`.

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

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

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

9 In the table, enter the following settings:

Legends
`real(Z) with impedance model`

Point Graph 2

1 In the **Model Builder** window, right-click **Flanged pipe: Z_rad vs. f** and choose **Point Graph**.

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

3 From the **Dataset** list, choose **Study 1 - Flanged pipe with impedance BC/Solution 1 (sol1)**.

4 Select Point 2 only.

5 Locate the **y-Axis Data** section. In the **Expression** text field, type `imag(acpr.imp1.Zn)`.

6 Locate the **Coloring and Style** section. From the **Color** list, choose **Red**.

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

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

9 In the table, enter the following settings:

Legends
`imag(Z) with impedance model`

10 In the **Flanged pipe: Z_rad vs. f** toolbar, click **Plot**.

Global 1

1 Right-click **Flanged pipe: Z_rad vs. f** and choose **Global**.

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

3 From the **Dataset** list, choose **Study 2 - Flanged pipe with PML/Solution 2 (sol2)**.

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

Expression	Unit	Description
intop1(p2)	N	

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

6 From the **Color** list, choose **Blue**.

7 Click to expand the **Legends** section. In the **Flanged pipe: Z_rad vs. f** toolbar, click **Plot**.

Global 2

1 Right-click **Flanged pipe: Z_rad vs. f** and choose **Global**.

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

3 From the **Dataset** list, choose **Study 2 - Flanged pipe with PML/Solution 2 (sol2)**.

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

Expression	Unit	Description
imag(intop1(p2)/intop1(acpr2.vz))	N*s/(m*m^2)	imag(Z) with PML

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

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

7 In the **Flanged pipe: Z_rad vs. f** toolbar, click **Plot**.

8 Click the **x-Axis Log Scale** button in the **Graphics** toolbar.

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

Flanged pipe: Z_rad vs. f

1 In the **Model Builder** window, click **Flanged pipe: Z_rad vs. f**.

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

3 From the **Position** list, choose **Lower right**.

Global 1

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

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

3 In the table, enter the following settings:

Expression	Unit	Description
intop1(p2)/intop1(acpr2.vz)	N*s/(m*m^2)	real(Z) with PML

4 In the **Flanged pipe: Z_rad vs. f** toolbar, click **Plot**.

You can create an alternative version of the plot by duplicating the plot group and changing the x-axis from f to k*a in all plots. See result in Figure 3.

COMPONENT 1 - FLANGED PIPE RADIATION (COMP1)

In the **Model Builder** window, collapse the **Component 1 - Flanged pipe radiation (comp1)** node.

Repeat the analysis for an unflanged pipe. Start by adding a new component.

ADD COMPONENT

In the **Model Builder** window, right-click the root node and choose **Add Component> 2D Axisymmetric**.

COMPONENT 2 - UNFLANGED PIPE RADIATION

In the **Settings** window for **Component**, type Component 2 - Unflanged pipe radiation in the **Label** text field.

Create an unflanged pipe geometry.

GEOMETRY 2

First create the pipe.

Rectangle 1 (r1)

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

2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

3 In the **Width** text field, type a.

4 In the **Height** text field, type L.

5 Locate the **Position** section. In the **z** text field, type -L.

Then create the surroundings.

Circle 1 (c1)

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

Add an external layer which you will use when applying the perfectly matched layer condition.

2 In the **Settings** window for **Circle**, locate the **Size and Shape** section.

3 In the **Radius** text field, type `6*a`.

4 In the **Sector angle** text field, type `180`.

5 Locate the **Rotation Angle** section. In the **Rotation** text field, type `-90`.

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

Layer name	Thickness (m)
`Layer 1`	`2*a`

7 Click **Build All Objects**.

Union 1 (uni1)

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

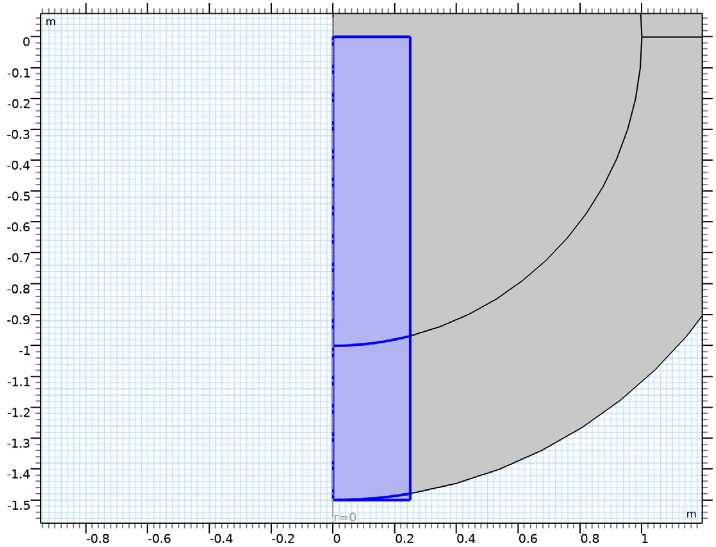
2 Click in the **Graphics** window and then press Ctrl+A to select both objects.

Delete overlaps between the pipe and the surroundings.

Form Composite Domains 1 (cmd1)

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

2 On the object **fin**, select Domains 1–3 only.



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

Now add physics and boundary conditions.

ADD PHYSICS

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

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

3 In the tree, select **Acoustics>Pressure Acoustics>Pressure Acoustics, Frequency Domain (acpr)**.

4 Click **Add to Component 2 - Unflanged Pipe Radiation** in the window toolbar.

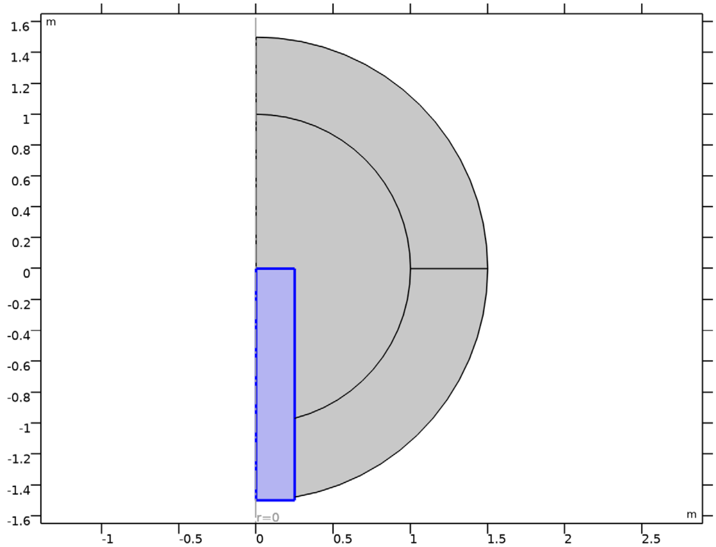
5 In the **Home** toolbar, click **Add Physics** to close the **Add Physics** window.

PRESSURE ACOUSTICS, FREQUENCY DOMAIN 3 - IMPEDANCE BC

1 In the **Settings** window for **Pressure Acoustics, Frequency Domain**, type `Pressure Acoustics, Frequency Domain 3 - impedance BC` in the **Label** text field.

2 Locate the **Domain Selection** section. From the **Selection** list, choose **Manual**.

3 Select Domain 1 only.



Normal Acceleration 1

1 Right-click **Component 2 - Unflanged pipe radiation (comp2)>Pressure Acoustics, Frequency Domain 3 - impedance BC** and choose **Normal Acceleration**.

2 Select Boundary 2 only.

It might be easier to select the correct boundary by using the **Selection List** window. To open this window, in the **Home** toolbar click **Windows** and choose **Selection List**. (If you are running the cross-platform desktop, you find **Windows** in the main menu.)

3 In the **Settings** window for **Normal Acceleration**, locate the **Normal Acceleration** section.

4 In the a_n text field, type `a0`.

Impedance 1

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

Remember to add the correct boundary impedance model.

2 Select Boundary 4 only.

3 In the **Settings** window for **Impedance**, locate the **Impedance** section.

4 From the **Impedance model** list, choose **Waveguide end impedance**.

5 From the list, choose **Unflanged pipe, circular**.

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

MATERIALS

Material 2 (mat2)

1 In the **Model Builder** window, under **Component 2 - Unflanged pipe radiation (comp2)** right-click **Materials** and choose **Blank Material**.

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

3 In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Density	rho	rho_air	kg/m³	Basic
Speed of sound	c	c_air	m/s	Basic

ADD PHYSICS

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

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

3 In the tree, select **Acoustics>Pressure Acoustics>Pressure Acoustics, Frequency Domain (acpr)**.

4 Click **Add to Component 2 - Unflanged Pipe Radiation** in the window toolbar.

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

PRESSURE ACOUSTICS, FREQUENCY DOMAIN 4 - PERFECTLY MATCHED LAYERS

In the **Settings** window for **Pressure Acoustics, Frequency Domain**, type `Pressure Acoustics, Frequency Domain 4 - perfectly matched layers` in the **Label** text field.

Normal Acceleration 1

1 Right-click **Component 2 - Unflanged pipe radiation (comp2)>Pressure Acoustics, Frequency Domain 4 - perfectly matched layers** and choose **Normal Acceleration**.

2 Select Boundary 2 only.

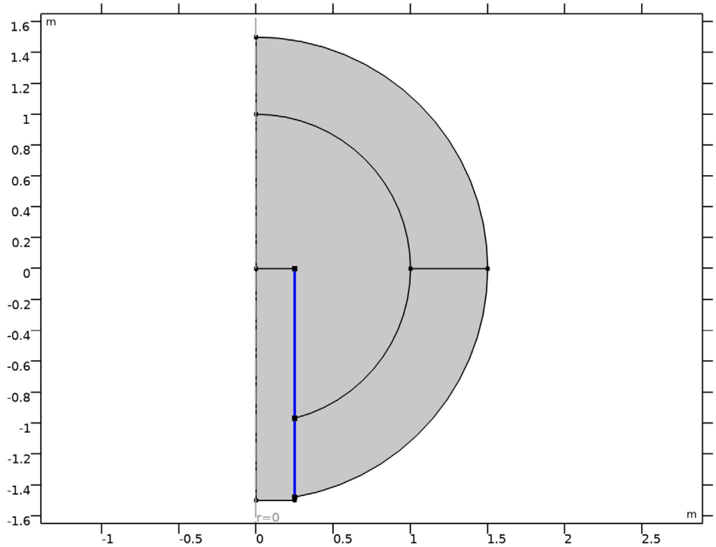
3 In the **Settings** window for **Normal Acceleration**, locate the **Normal Acceleration** section.

4 In the a_n text field, type `a0`.

Interior Sound Hard Boundary (Wall) 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Interior Sound Hard Boundary (Wall)**.

2 Select Boundaries 7 and 8 only.



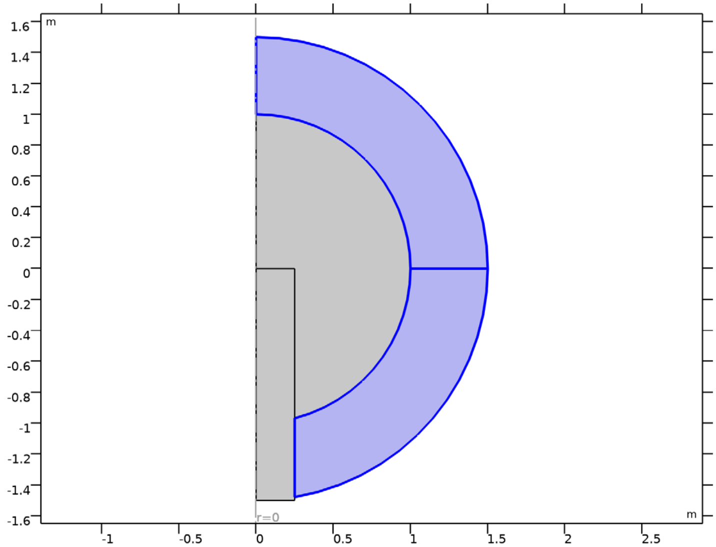
Now define the perfectly matched layer condition and a nonlocal integration coupling acting on the pipe outlet.

DEFINITIONS (COMP2)

Perfectly Matched Layer 2 (pml2)

1 In the **Definitions** toolbar, click **Perfectly Matched Layer**.

2 Select Domains 3 and 4 only.



3 In the **Settings** window for **Perfectly Matched Layer**, locate the **Scaling** section.

4 From the **Physics** list, choose **Pressure Acoustics, Frequency Domain 4 - perfectly matched layers (acpr4)**.

5 In the **PML scaling factor** text field, type `0.5`.

6 In the **PML scaling curvature parameter** text field, type `5`.

7 From the **Coordinate stretching type** list, choose **Rational**.

DEFINITIONS (COMP2)

Integration 2 (intop2)

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

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

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

4 Select Boundary 4 only.

Create the mesh.

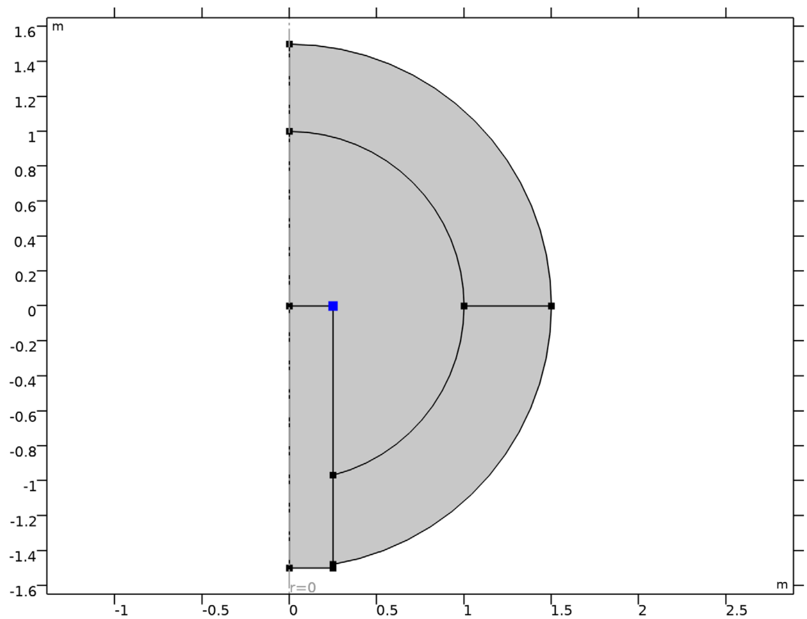
MESH 2

Free Triangular 1

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

Size 1

1. Right-click **Free Triangular 1** and choose **Size**.
2. In the **Settings** window for **Size**, locate the **Element Size** section.
3. Click the **Custom** button.
4. Locate the **Geometric Entity Selection** section. From the **Geometric entity level** list, choose **Point**.
5. Select Point 8 only.



6. Locate the **Element Size Parameters** section.
7. Select the **Maximum element size** check box. In the associated text field, type `hmax/15`.

Free Triangular 1

1. In the **Model Builder** window, click **Free Triangular 1**.
2. In the **Settings** window for **Free Triangular**, locate the **Domain Selection** section.
3. From the **Geometric entity level** list, choose **Domain**.
4. Select Domains 1 and 2 only.

Size

1. In the **Model Builder** window, click **Size**.
2. In the **Settings** window for **Size**, locate the **Element Size** section.

3 Click the **Custom** button.

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

5 In the **Minimum element size** text field, type `6.0E-4`.

Mapped 1

1 In the **Mesh** toolbar, click **Mapped**.

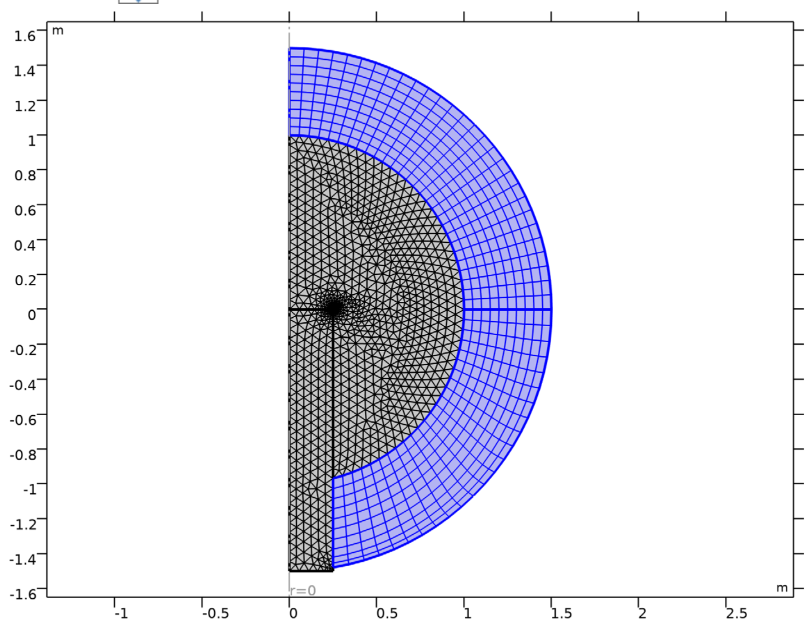
2 In the **Settings** window for **Mapped**, locate the **Domain Selection** section.

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

4 Select Domains 3 and 4 only.

5 Click **Build All**.

6 Click the **Zoom Extents** button in the **Graphics** toolbar.



Mesh used to simulate the unflanged pipe. The highlighted regions are used to apply the perfectly matched layer condition.

Next, add two studies: one for the impedance-based model and another for the model with perfectly matched layers. For each study, keep only one physics model (impedance-based or with perfectly matched layers) and immediately disable all other physics models. This is similar to what you did for the flanged pipe model in **Component 1**.

ADD STUDY

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

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

3 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies> Frequency Domain**.

4 Find the **Physics interfaces in study** subsection. In the table, enter the following settings:

Physics	Solve
Pressure Acoustics, Frequency Domain - impedance model (acpr)	√
Pressure Acoustics, Frequency Domain 2 - perfectly matched layers (acpr2)	√
Pressure Acoustics, Frequency Domain 3 - impedance BC (acpr3)	√
Pressure Acoustics, Frequency Domain 4 - perfectly matched layers (acpr4)	√

5 Click **Add Study** in the window toolbar.

6 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies> Frequency Domain**.

7 Find the **Physics interfaces in study** subsection. In the table, enter the following settings:

Physics	Solve
Pressure Acoustics, Frequency Domain - impedance model (acpr)	√
Pressure Acoustics, Frequency Domain 2 - perfectly matched layers (acpr2)	√
Pressure Acoustics, Frequency Domain 3 - impedance BC (acpr3)	√
Pressure Acoustics, Frequency Domain 4 - perfectly matched layers (acpr4)	√

8 Click **Add Study** in the window toolbar.

9 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 4

Step 1: Frequency Domain

Set up the studies.

STUDY 3 - UNFLANGED PIPE WITH IMPEDANCE BC

1 In the **Model Builder** window, click **Study 3**.

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

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

4 In the **Label** text field, type `Study 3 - Unflanged pipe with impedance BC`.

Step 1: Frequency Domain

1 In the **Model Builder** window, under **Study 3 - Unflanged pipe with impedance BC** 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 **ISO preferred frequencies** from the **Entry method** list.

5 In the **Start frequency** text field, type `fmin`.

6 In the **Stop frequency** text field, type `fmax`.

7 From the **Interval** list, choose **1/24 octave**.

8 Click **Replace**.

9 In the **Home** toolbar, click **Compute**.

STUDY 4 - UNFLANGED PIPE WITH PML

1 In the **Model Builder** window, click **Study 4**.

2 In the **Settings** window for **Study**, type `Study 4 - Unflanged pipe with PML` in the **Label** text field.

3 Locate the **Study Settings** section. Clear the **Generate default plots** check box.

Step 1: Frequency Domain

1 In the **Model Builder** window, under **Study 4 - Unflanged pipe with PML** 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 **ISO preferred frequencies** from the **Entry method** list.

5 In the **Start frequency** text field, type `fmin`.

6 In the **Stop frequency** text field, type `fmax`.

7 From the **Interval** list, choose **1/24 octave**.

8 Click **Replace**.

9 In the **Home** toolbar, click **Compute**.

RESULTS

Now compare the pipe outlet impedance from the two models in a plot. The result is shown in Figure 5.

Unflanged pipe: Z_rad vs. f

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

2 In the **Settings** window for **1D Plot Group**, type `Unflanged pipe: Z_rad vs. f` 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 `Z_rad [Pa*s/m]`.

8 Locate the **Legend** section. From the **Position** list, choose **Lower right**.

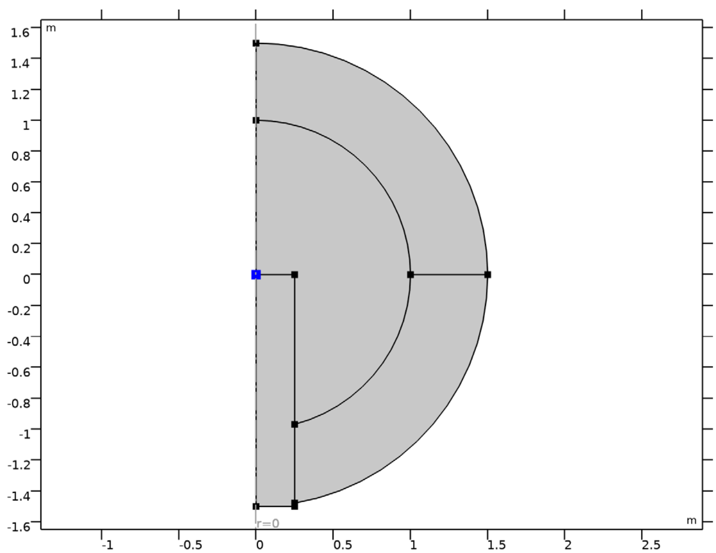
Point Graph 1

1 Right-click **Unflanged pipe: Z_rad vs. f** and choose **Point Graph**.

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

3 From the **Dataset** list, choose **Study 3 - Unflanged pipe with impedance BC/ Solution 3 (4) (sol3)**.

4 Select Point 2 only.



5 Locate the **y-Axis Data** section. In the **Expression** text field, type `real(acpr3.imp1.Zn)`.

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

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

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

9 In the table, enter the following settings:

Legends
`real(Z) impedance model`

Point Graph 2

1 In the **Model Builder** window, right-click **Unflanged pipe: Z_rad vs. f** and choose **Point Graph**.

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

3 From the **Dataset** list, choose **Study 3 - Unflanged pipe with impedance BC/ Solution 3 (4) (sol3)**.

4 Select Point 2 only.

5 Locate the **y-Axis Data** section. In the **Expression** text field, type `imag(acpr3.imp1.Zn)`.

6 Locate the **Coloring and Style** section. From the **Color** list, choose **Red**.

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

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

9 In the table, enter the following settings:

Legends
`imag(Z) impedance model`

10 In the **Unflanged pipe: Z_rad vs. f** toolbar, click **Plot**.

Global 1

1 Right-click **Unflanged pipe: Z_rad vs. f** and choose **Global**.

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

3 From the **Dataset** list, choose **Study 4 - Unflanged pipe with PML/Solution 4 (6) (sol4)**.

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

Expression	Unit	Description
`intop2(p4)/intop2(acpr4.vz)`	`N*s/(m*m^2)`	`real(Z) with PML`

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

6 From the **Color** list, choose **Blue**.

7 In the **Unflanged pipe: Z_rad vs. f** toolbar, click **Plot**.

Global 2

1 Right-click **Unflanged pipe: Z_rad vs. f** and choose **Global**.

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

3 From the **Dataset** list, choose **Study 4 - Unflanged pipe with PML/Solution 4 (6) (sol4)**.

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

Expression	Unit	Description
`imag(intop2(p4)/ intop2(acpr4.vz))`	`N*s/(m*m^2)`	`imag(Z) with PML`

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

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

7 In the **Unflanged pipe: Z_rad vs. f** toolbar, click **Plot**.

8 Click the **x-Axis Log Scale** button in the **Graphics** toolbar.

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

You can duplicate the plot group and change the x-axis from `f` to `k*a` to replot the result as shown in Figure 6.

Compare the centerline outlet pressure using both the impedance-based model and the model with perfectly matched layers. Do this for both the flanged and unflanged pipes. See the results in Figure 4 and Figure 7.

Flanged pipe: centerline outlet 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 `Flanged pipe: centerline outlet pressure` 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**.

Point Graph 1

1 Right-click **Flanged pipe: centerline outlet pressure** and choose **Point Graph**.

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

3 From the **Dataset** list, choose **Study 1 - Flanged pipe with impedance BC/Solution 1 (sol1)**.

4 Select Point 2 only.

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

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

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

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

9 In the table, enter the following settings:

Legends
`real(p) with impedance`

10 In the **Flanged pipe: centerline outlet pressure** toolbar, click **Plot**.

Point Graph 2

1 In the **Model Builder** window, right-click **Flanged pipe: centerline outlet pressure** and choose **Point Graph**.

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

3 From the **Dataset** list, choose **Study 1 - Flanged pipe with impedance BC/Solution 1 (sol1)**.

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

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

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

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

8 In the table, enter the following settings:

Legends
`imag(p) with impedance`

9 In the **Flanged pipe: centerline outlet pressure** toolbar, click **Plot**.

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

11 Select Point 2 only.

12 In the **Flanged pipe: centerline outlet pressure** toolbar, click **Plot**.

Point Graph 3

1 Right-click **Flanged pipe: centerline outlet pressure** and choose **Point Graph**.

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

3 From the **Dataset** list, choose **Study 2 - Flanged pipe with PML/Solution 2 (sol2)**.

4 Select Point 2 only.

5 Locate the **y-Axis Data** section. In the **Expression** text field, type `real(acpr2.p_t)`.

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

7 Find the **Line style** subsection. From the **Line** list, choose **None**.

8 Find the **Line markers** subsection. From the **Marker** list, choose **Circle**.

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

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

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
`real(p) with PML`

14 In the **Flanged pipe: centerline outlet pressure** toolbar, click **Plot**.

Point Graph 4

1 Right-click **Flanged pipe: centerline outlet pressure** and choose **Point Graph**.

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

3 From the **Dataset** list, choose **Study 2 - Flanged pipe with PML/Solution 2 (sol2)**.

4 Select Point 2 only.

5 Locate the **y-Axis Data** section. In the **Expression** text field, type `imag(acpr2.p_t)`.

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

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

8 Find the **Line markers** subsection. From the **Marker** list, choose **Circle**.

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

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

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
`imag(p) with PML`

14 In the **Flanged pipe: centerline outlet pressure** toolbar, click **Plot**.

15 Click the **x-Axis Log Scale** button in the **Graphics** toolbar.

Now the unflanged pipe.

Unflanged pipe: centerline outlet 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 `Unflanged pipe: centerline outlet pressure` 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**.

Point Graph 1

1 Right-click **Unflanged pipe: centerline outlet pressure** and choose **Point Graph**.

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

3 From the **Dataset** list, choose **Study 3 - Unflanged pipe with impedance BC/ Solution 3 (4) (sol3)**.

4 Select Point 2 only.

5 Locate the **y-Axis Data** section. In the **Expression** text field, type `real(acpr3.p_t)`.

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

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

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

9 In the table, enter the following settings:

Legends
`real(p) with impedance`

10 In the **Unflanged pipe: centerline outlet pressure** toolbar, click **Plot**.

Point Graph 2

1 In the **Model Builder** window, right-click **Unflanged pipe: centerline outlet pressure** and choose **Point Graph**.

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

3 From the **Dataset** list, choose **Study 3 - Unflanged pipe with impedance BC/ Solution 3 (4) (sol3)**.

4 Select Point 2 only.

5 Locate the **y-Axis Data** section. In the **Expression** text field, type `imag(acpr3.p_t)`.

6 Locate the **Coloring and Style** section. From the **Color** list, choose **Red**.

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

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

9 In the table, enter the following settings:

Legends
`imag(p) with impedance`

10 In the **Unflanged pipe: centerline outlet pressure** toolbar, click **Plot**.

Point Graph 3

1 Right-click **Unflanged pipe: centerline outlet pressure** and choose **Point Graph**.

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

3 From the **Dataset** list, choose **Study 4 - Unflanged pipe with PML/Solution 4 (6) (sol4)**.

4 Select Point 2 only.

5 Locate the **y-Axis Data** section. In the **Expression** text field, type `real(acpr4.p_t)`.

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

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

8 Find the **Line markers** subsection. From the **Marker** list, choose **Circle**.

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

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

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

12 In the table, enter the following settings:

Legends
`real(p) with PML`

13 In the **Unflanged pipe: centerline outlet pressure** toolbar, click **Plot**.

14 Locate the **Coloring and Style** section. In the **Number** text field, type `100`.

15 In the **Unflanged pipe: centerline outlet pressure** toolbar, click **Plot**.

Point Graph 4

1 Right-click **Unflanged pipe: centerline outlet pressure** and choose **Point Graph**.

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

3 From the **Dataset** list, choose **Study 4 - Unflanged pipe with PML/Solution 4 (6) (sol4)**.

4 Select Point 2 only.

5 Locate the **y-Axis Data** section. In the **Expression** text field, type `imag(acpr4.p_t)`.

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

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

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

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

10 In the table, enter the following settings:

Legends
`imag(p) with PML`

11 In the **Unflanged pipe: centerline outlet pressure** toolbar, click **Plot**.

12 Locate the **Coloring and Style** section. Find the **Line markers** subsection. From the **Marker** list, choose **Circle**.

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

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

15 In the **Unflanged pipe: centerline outlet pressure** toolbar, click **Plot**.

16 Click the **x-Axis Log Scale** button in the **Graphics** toolbar.

Disable the unflanged interfaces in the first two studies, so that you can run them later.

STUDY 1 - FLANGED PIPE WITH IMPEDANCE BC

Step 1: Frequency Domain

1 In the **Model Builder** window, under **Study 1 - Flanged pipe with impedance BC** click **Step 1: Frequency Domain**.

2 In the **Settings** window for **Frequency Domain**, locate the **Physics and Variables Selection** section.

3 In the table, enter the following settings:

Physics interface	**Solve for**
Pressure Acoustics, Frequency Domain - impedance model (acpr)	√
Pressure Acoustics, Frequency Domain 2 - perfectly matched layers (acpr2)	
Pressure Acoustics, Frequency Domain 3 - impedance BC (acpr3)	
Pressure Acoustics, Frequency Domain 4 - perfectly matched layers (acpr4)	

STUDY 2 - FLANGED PIPE WITH PML

Step 1: Frequency Domain

1 In the **Model Builder** window, under **Study 2 - Flanged pipe with PML** click **Step 1: Frequency Domain**.
2 In the **Settings** window for **Frequency Domain**, locate the **Physics and Variables Selection** section.
3 In the table, enter the following settings:

Physics interface	Solve for
Pressure Acoustics, Frequency Domain - impedance model (acpr)	
Pressure Acoustics, Frequency Domain 2 - perfectly matched layers (acpr2)	√
Pressure Acoustics, Frequency Domain 3 - impedance BC (acpr3)	
Pressure Acoustics, Frequency Domain 4 - perfectly matched layers (acpr4)	

Solving Study 3 and Study 4 generates datasets based on the results in Component 1, where no physics is solved for. You can remove the unused datasets to clean up the model.

RESULTS

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

Study 3 - Unflanged pipe with impedance BC/Solution 3 (3) (sol3), Study 4 - Unflanged pipe with PML/Solution 4 (5) (sol4)

1 In the **Model Builder** window, under **Results>Datasets**, Ctrl-click to select **Study 3 - Unflanged pipe with impedance BC/Solution 3 (3) (sol3)** and **Study 4 - Unflanged pipe with PML/Solution 4 (5) (sol4)**.
2 Right-click and choose **Delete**.