



Model created in COMSOL Multiphysics 6.4

# Point Source in a 2D Jet: Radiation and Refraction of Sound Waves Through a 2D Shear Layer

## Introduction

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This is a benchmark model for the Linearized Euler interfaces in the Acoustics Module. The model is from the NASA workshop “Fourth Computational Aeroacoustics (CAA) Workshop on Benchmark Problems (2004).” The model solved here is problem 1 in category 4 on “Sound Transmission and Radiation”. The model results are compared with an analytical solution by Agarwal and others (see [Ref. 1](#) and [Ref. 2](#)).

A point source is located in a narrow 2D jet of Mach 0.8. The model investigates the propagation of acoustic and nonacoustic waves in the flow, solving the linearized Euler equations in both the frequency and the time domain. Because of the nature of the background flow, radiation and refraction of the sound waves through the narrow 2D shear layer of the narrow jet, need to be captured accurately. The model also demonstrates how instability waves are suppressed in frequency domain models while they will grow and propagate in the time domain for the linearized Euler model.

## Model Definition

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A narrow Gaussian shaped point-like source  $S$  is located in a narrow jet, the background mean flow,  $\mathbf{u}_0 = (u_0, v_0)$ , centered at the x-axis. A symmetry conditions is applied at  $y = 0$ . We have

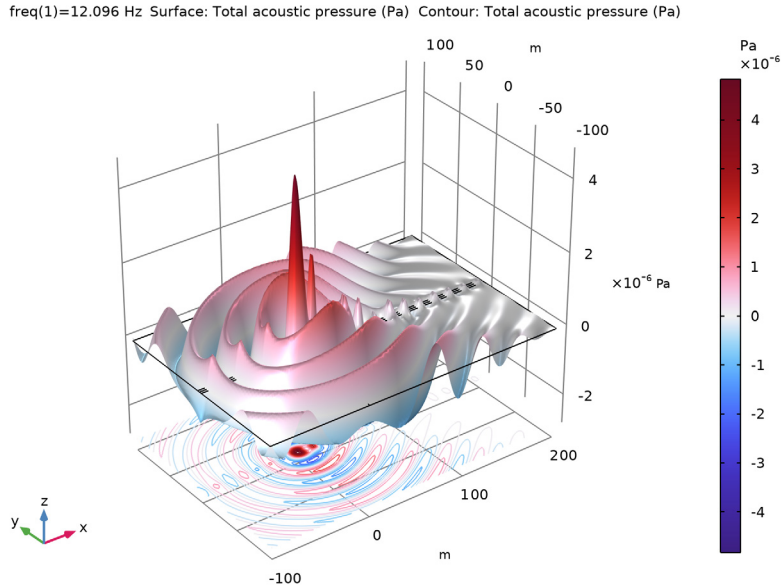
$$\begin{aligned} S(x, y) &= A \exp(-(B_x x^2 + B_y y^2)) \\ S(x, y, t) &= S(x, y) \cos(2\pi f t) \\ u_0 &= u_j \exp\left(-\log(2) \left(\frac{y}{b}\right)^2\right) \quad v_0 = 0 \\ u_j &= M_j c_j \quad c_j = \sqrt{\gamma R_s T_j} \end{aligned} \tag{1}$$

where the subscript “j” stands for the jet properties. The details of the model definitions and constants are found in [Ref. 2](#). The constants are defined in the model parameters under **Global Definitions > Parameters I - Model** and the source and jet variables are found in **Definitions > Variables I - Flow Jet and Source**.

The model is solved both in the frequency domain, with a given angular frequency of  $\omega_0 = 76$  rad/s. In the time domain using a harmonics source as defined above. The linearized Euler equations describe the propagation of the compressible acoustic waves, but they also support non-acoustic waves/instabilities, that can propagate. In the frequency domain instability waves cannot be triggered as the system is forced at the given (real) frequency, and no waves can grow. This is not the case in the time domain as is also seen from the model results.

## Results and Discussion

The acoustic pressure is depicted for the frequency domain model in [Figure 1](#). The  $x$  and  $y$ -velocities (acoustic particle velocities) are depicted in [Figure 2](#). Still for the frequency domain model, the pressure along the  $y = 0$  m and the  $y = 15$  m lines is depicted in [Figure 3](#). In [Figure 4](#) the results are compared to the analytical reference solution given in [Ref. 1](#). The results show good agreement.



*Figure 1: Pressure distribution in the frequency domain model. No instability waves are growing and convected by the jet.*

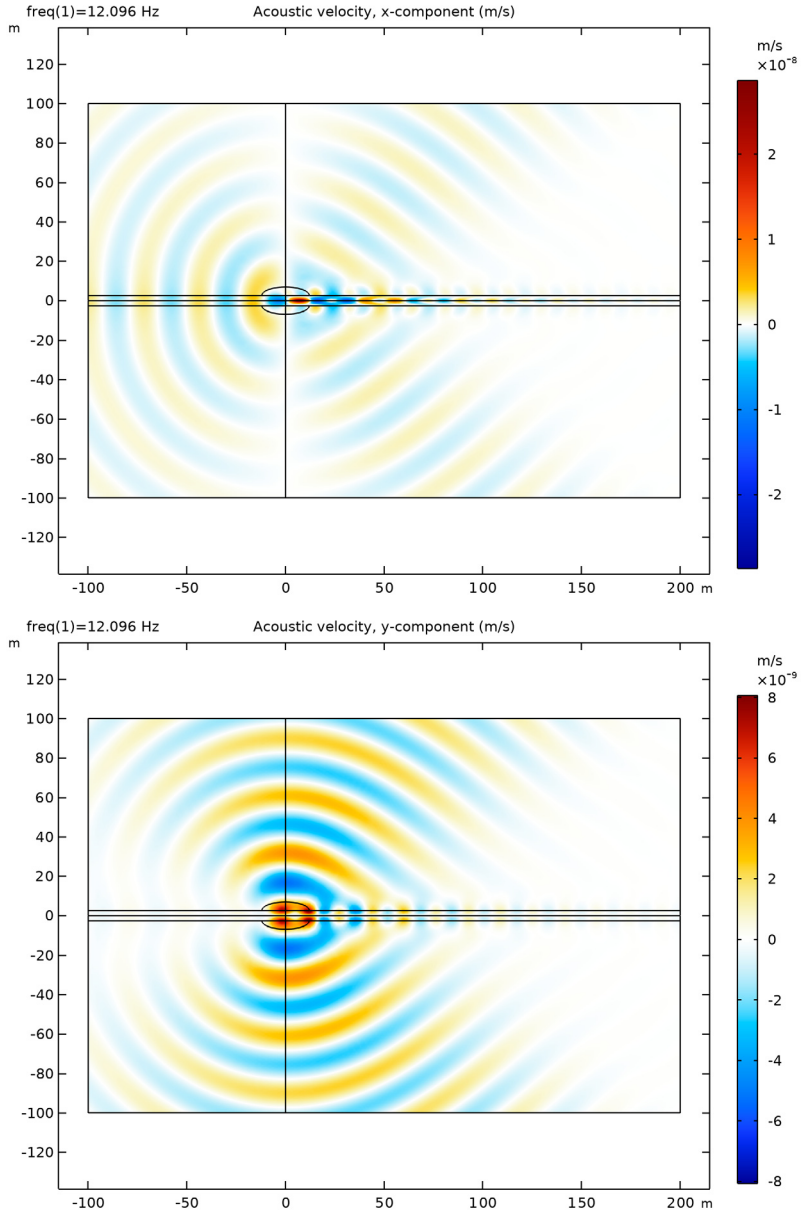


Figure 2: Real part of the  $x$ -velocity (top) and  $y$ -velocity (bottom) for the frequency domain model.

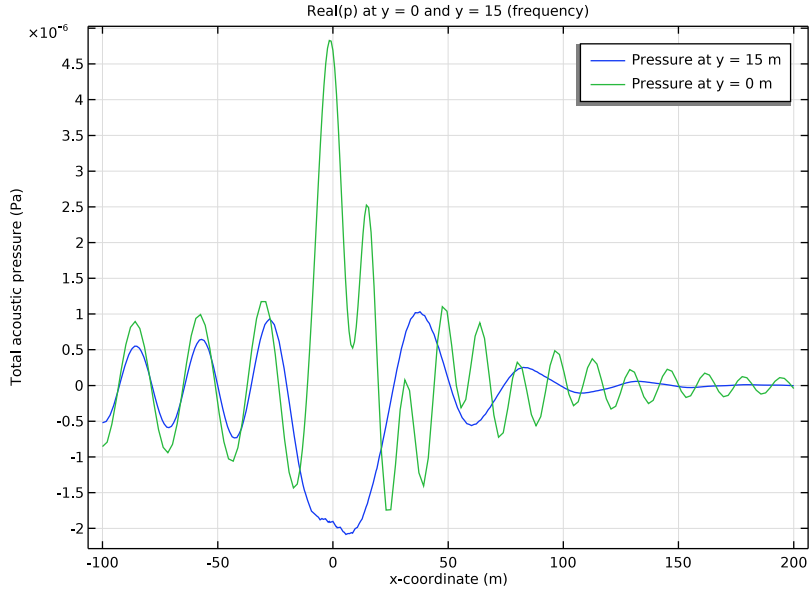


Figure 3: Pressure (real part) along the lines  $y = 15$  m and  $y = 0$  m.

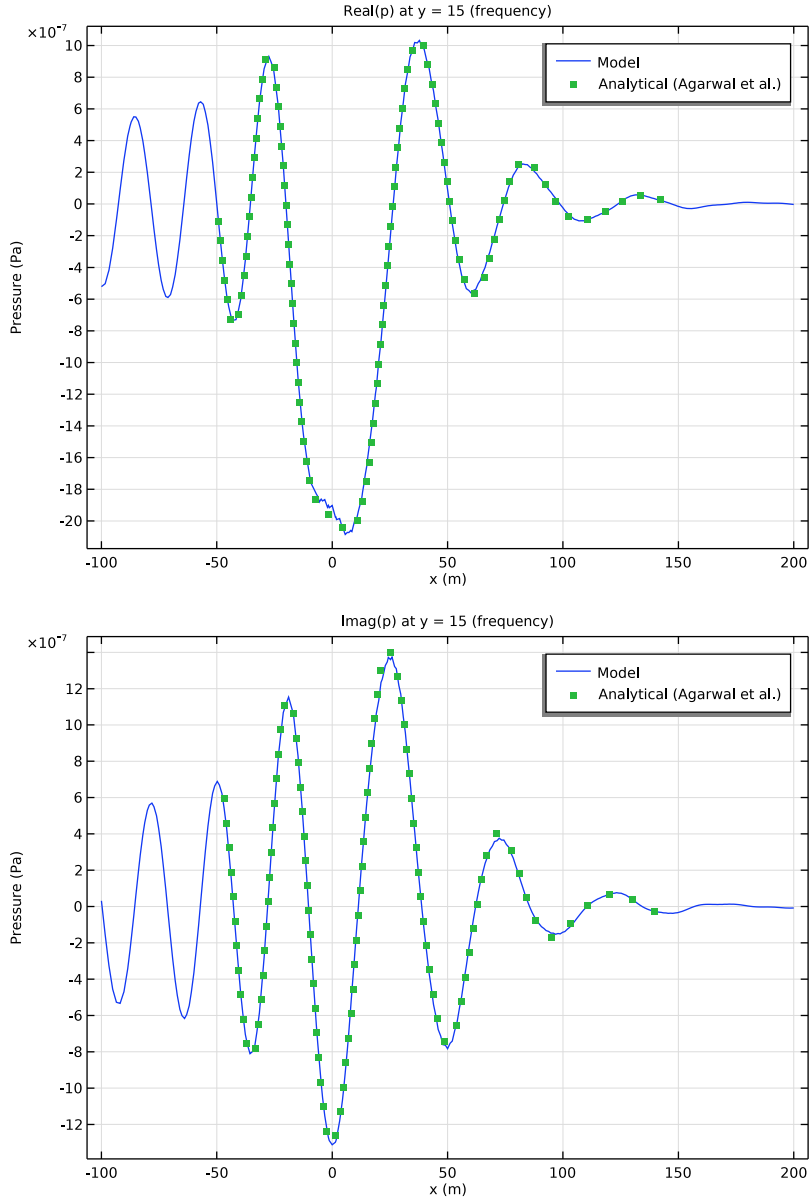
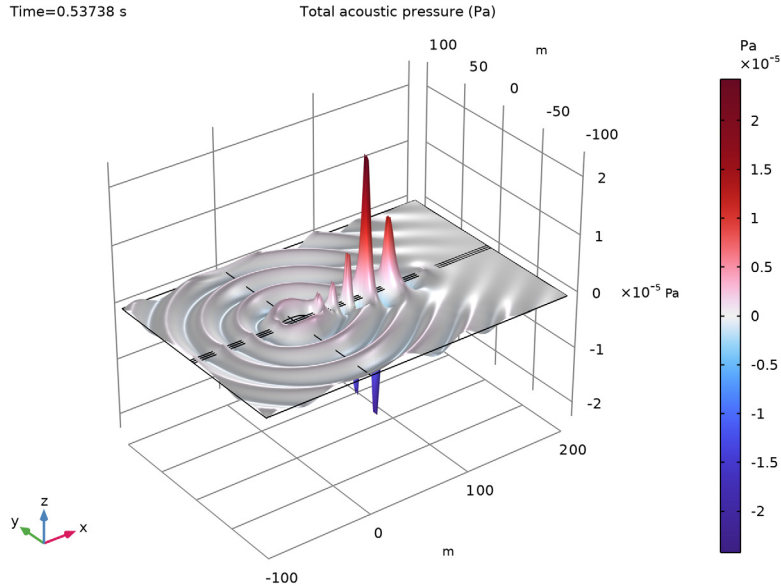


Figure 4: Real part (top) and imaginary part (bottom) of the pressure compared to the analytical solutions (frequency domain).



*Figure 5: Pressure distribution at  $t = 0.537$  s for the transient model. The instability is seen to grow and gets convected by the jet along the symmetry line.*

As opposed to the frequency domain, the time domain solutions, seen in [Figure 5](#), shows the onset of a strong instability that moves at the convective speed of the jet (close to the symmetry plane at  $y = 0$  m). See more time frames in the model. In [Figure 6](#) the time domain solution and frequency domain solutions are compared to each other, and in one case also to the analytical solution. Downstream of the source, where the instability wave grows, the solutions cannot be compared (the graph is zoomed). The results show good agreement in the regions where no instability is propagating.

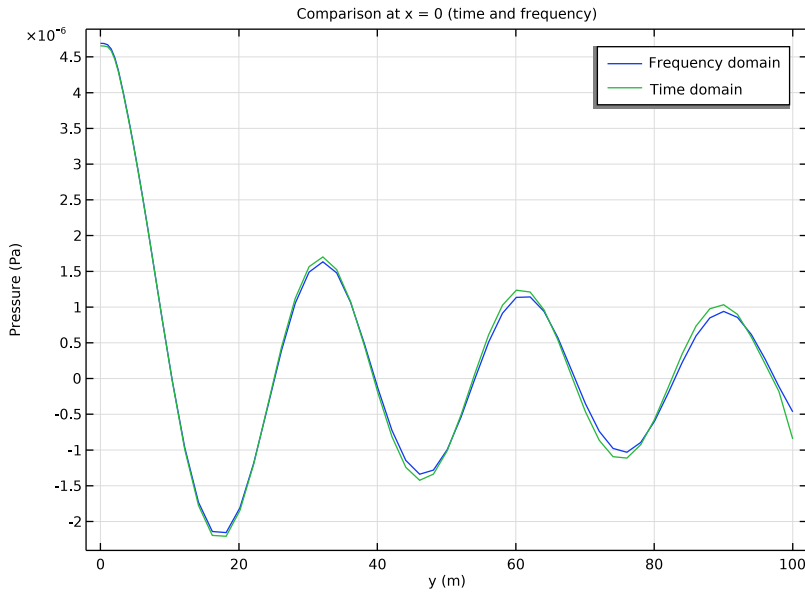
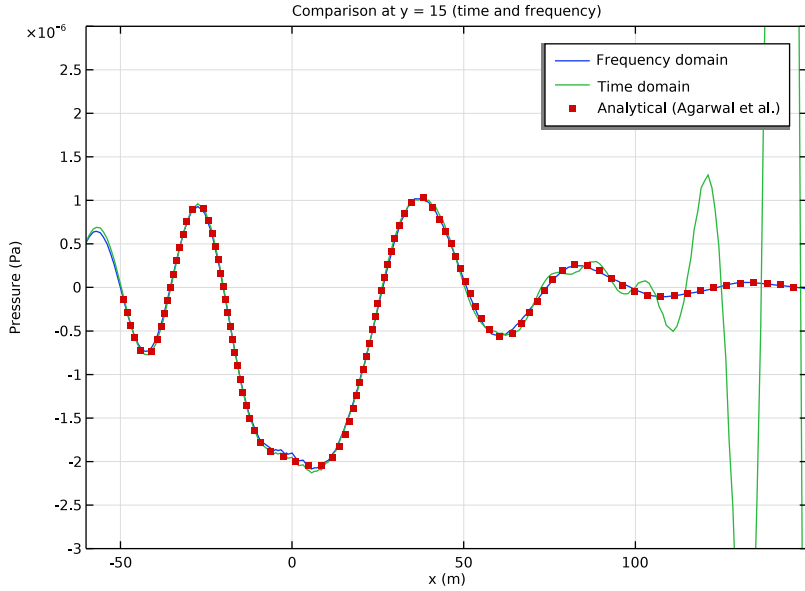


Figure 6: Comparison of the frequency domain (at the given phase), time domain, and analytical solution along the  $y = 15$  m line (top) and the  $x = 0$  m (bottom).

## References

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1. A. Agarwal, P.J. Morris, and R. Mani, “Calculation of Sound Propagation in Nonuniform Flows: Suppression of Instability Waves,” *AIAA J.*, vol. 42, no. 1, pp. 80–88, 2004; [doi.org/10.2514/1.619](https://doi.org/10.2514/1.619).
  2. “Fourth Computational Aeroacoustics (CAA) Workshop on Benchmark Problems” NASA/CP—2004-212954.
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**Application Library path:** `Acoustics_Module/Aeroacoustics_and_Noise/point_source_2d_jet`


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## Modeling Instructions




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

### NEW

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


### MODEL WIZARD

- 1 In the **Model Wizard** window, click  **2D**.
- 2 In the **Select Physics** tree, select **Acoustics > Aeroacoustics > Linearized Euler, Frequency Domain (lef)**.
- 3 Click **Add**.
- 4 In the **Select Physics** tree, select **Acoustics > Aeroacoustics > Linearized Euler, Transient (let)**.
- 5 Click **Add**.
- 6 Click  **Study**.
- 7 In the **Select Study** tree, select **Empty Study**.
- 8 Click  **Done**.



### GLOBAL DEFINITIONS

#### *Parameters I - Model*

- 1 In the **Model Builder** window, under **Global Definitions** click **Parameters I**.
- 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 `point_source_2d_jet_parameters.txt`.
- 5 In the **Label** text field, type `Parameters 1 - Model`.

#### *Parameters 2 - Geometry*

- 1 In the **Home** toolbar, click  **Parameters** and choose **Add > Parameters**.
- 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 `point_source_2d_jet_geometry_parameters.txt`.
- 5 In the **Label** text field, type `Parameters 2 - Geometry`.


#### *Interpolation 1 (int1)*

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

### **STUDY 1**

In the **Model Builder** window, collapse the **Study 1** node.

### **GLOBAL DEFINITIONS**

- 1 In the **Model Builder** window, under **Global Definitions** click **Interpolation 1 (int1)**.
- 2 In the **Settings** window for **Interpolation**, locate the **Definition** section.
- 3 From the **Data source** list, choose **File**.
- 4 Click  **Browse**.
- 5 Browse to the model's Application Libraries folder and double-click the file `point_source_2d_jet_analytical.txt`.
- 6 Locate the **Data Column Settings** section. In the table, click to select the cell at row number 1 and column number 3.
- 7 In the **Unit** text field, type `m`.
- 8 In the table, enter the following settings:

| Columns  | Type            | Settings                 |
|----------|-----------------|--------------------------|
| Column 2 | Function values | Function name=int_p_real |

- 9 In the **Name** text field, type `int_p_real`.
- 10 In the **Unit** text field, type `Pa`.

11 In the table, enter the following settings:

| Columns  | Type            | Settings                 |
|----------|-----------------|--------------------------|
| Column 3 | Function values | Function name=int_p_imag |


12 In the **Name** text field, type int\_p\_imag.

13 In the **Unit** text field, type Pa.

14 In the table, enter the following settings:

| Columns  | Type           | Settings |
|----------|----------------|----------|
| Column 4 | Ignored column |          |

15 Locate the **Interpolation and Extrapolation** section. From the **Interpolation** list, choose **Piecewise cubic**.

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

Proceed and create the geometry including domains for the PML and Absorbing Layer as well as domains used to set up a good mesh for the source and narrow jet.

## GEOMETRY I

*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  $(X_{\max} - X_{\min}) + 2 * L_{pml}$ .

4 In the **Height** text field, type  $Y_{\max} + L_{pml}$ .

5 Locate the **Position** section. In the **x** text field, type  $X_{\min} - L_{pml}$ .

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

| Layer name | Thickness (m) |
|------------|---------------|
| Layer 1    | $L_{pml}$     |


7 Select the **Layers to the left** checkbox.

8 Select the **Layers to the right** checkbox.


9 Clear the **Layers on bottom** checkbox.

10 Select the **Layers on top** checkbox.


11 Click  **Build Selected**.

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


*Rectangle 2 (r2)*

- 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  $X_{max}$ .
- 4 In the **Height** text field, type  $Y_{max} + L_{pml}$ .


*Rectangle 3 (r3)*

- 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  $(X_{max} - X_{min}) + 2 * L_{pml}$ .
- 4 In the **Height** text field, type  $2 * b$ .
- 5 Locate the **Position** section. In the **x** text field, type  $X_{min} - L_{pml}$ .

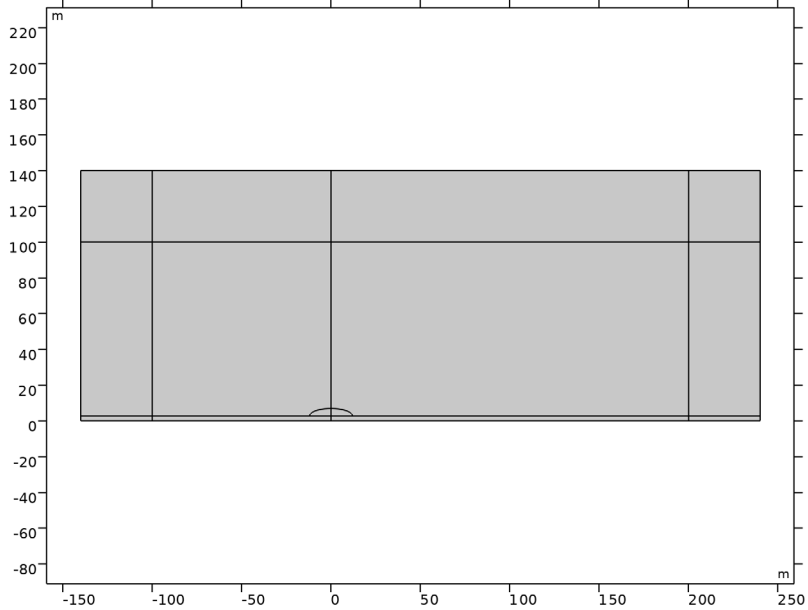
*Ellipse 1 (e1)*

- 1 In the **Geometry** toolbar, click  **Ellipse**.
- 2 In the **Settings** window for **Ellipse**, locate the **Size and Shape** section.
- 3 In the **a-semiaxis** text field, type  $2 * \sqrt{1/B_x}$ .
- 4 In the **b-semiaxis** text field, type  $2 * \sqrt{1/B_y}$ .
- 5 In the **Sector angle** text field, type 180.
- 6 Locate the **Position** section. In the **y** text field, type  $2 * b$ .

*Form Union (fn)*

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

2 In the **Model Builder** window, click **Form Union (fin)**.



Add the air material.

#### ADD MATERIAL FROM LIBRARY

In the **Home** toolbar, click  **Windows** and choose **Add Material from Library**.

#### ADD MATERIAL

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

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

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

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

#### MATERIALS

*Air (mat1)*


Define selections and the Perfectly Matched Layer (PML) used in the frequency domain as well as the Absorbing Layer (AL) used in the time domain.

## DEFINITIONS


### *PML and AL*

- 1 In the **Model Builder** window, expand the **Component 1 (comp1)** > **Definitions** node.
- 2 Right-click **Definitions** and choose **Selections** > **Explicit**.
- 3 In the **Settings** window for **Explicit**, type PML and AL in the **Label** text field.
- 4 Select Domains 1–3, 6, and 11–14 only.

### *Symmetry*


- 1 In the **Definitions** toolbar, click  **Explicit**.
- 2 In the **Settings** window for **Explicit**, type Symmetry in the **Label** text field.
- 3 Locate the **Input Entities** section. From the **Geometric entity level** list, choose **Boundary**.
- 4 Select Boundaries 2, 9, 17, and 26 only.

### *Perfectly Matched Layer 1 (pml1)*

- 1 In the **Definitions** toolbar, click  **Perfectly Matched Layer**.
- 2 In the **Settings** window for **Perfectly Matched Layer**, locate the **Domain Selection** section.
- 3 From the **Selection** list, choose **PML and AL**.
- 4 Locate the **Scaling** section. In the **PML scaling curvature parameter** text field, type 3.


## ARTIFICIAL DOMAINS


### *Absorbing Layer 1 (abl)*

- 1 In the **Definitions** toolbar, click  **Absorbing Layer**.
- 2 In the **Settings** window for **Absorbing Layer**, locate the **Domain Selection** section.
- 3 From the **Selection** list, choose **PML and AL**.

## DEFINITIONS

### *Variables 1 - Flow Jet and Source*

- 1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Definitions** and choose **Variables**.
- 2 In the **Settings** window for **Variables**, locate the **Variables** section.
- 3 Click  **Load from File**.
- 4 Browse to the model's Application Libraries folder and double-click the file `point_source_2d_jet_variables.txt`.
- 5 In the **Label** text field, type Variables 1 - Flow Jet and Source.

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

Now, set up the physics, both the frequency domain and the time domain interfaces.

### **LINEARIZED EULER, FREQUENCY DOMAIN (LEF)**


#### *Linearized Euler Model I*

- 1 In the **Model Builder** window, under **Component 1 (comp1)** > **Linearized Euler**, **Frequency Domain (lef)** click **Linearized Euler Model I**.
- 2 In the **Settings** window for **Linearized Euler Model**, locate the **Model Input** section.
- 3 In the  $p_0$  text field, type  $p_0$ .
- 4 In the  $T_0$  text field, type  $T_0$ .
- 5 Specify the  $\mathbf{u}_0$  vector as


|       |     |
|-------|-----|
| $u_0$ | $x$ |
| $v_0$ | $y$ |

- 6 Locate the **Fluid Properties** section. From the  $\rho_0$  list, choose **User defined**. In the associated text field, type  $\rho_0$ .

#### *Symmetry I*

- 1 In the **Physics** toolbar, click  **Boundaries** and choose **Symmetry**.
- 2 In the **Settings** window for **Symmetry**, locate the **Boundary Selection** section.
- 3 From the **Selection** list, choose **Symmetry**.

#### *Domain Sources I*

- 1 In the **Physics** toolbar, click  **Domains** and choose **Domain Sources**.
- 2 Select Domains 4, 5, and 7–10 only.
- 3 In the **Settings** window for **Domain Sources**, locate the **Domain Sources** section.
- 4 In the  $p_{rc}$  text field, type  $S$ .

### **LINEARIZED EULER, TRANSIENT (LET)**

- 1 In the **Model Builder** window, under **Component 1 (comp1)** click **Linearized Euler**, **Transient (let)**.
- 2 In the **Settings** window for **Linearized Euler, Transient**, locate the **Transient Solver Settings** section.
- 3 In the  $f_{\max, sol}$  text field, type  $f_0$ .


### Linearized Euler Model I

- 1 In the **Model Builder** window, under **Component 1 (comp1) > Linearized Euler, Transient (let)** click **Linearized Euler Model I**.
- 2 In the **Settings** window for **Linearized Euler Model**, locate the **Model Input** section.
- 3 In the  $p_0$  text field, type  $p_0$ .
- 4 In the  $T_0$  text field, type  $T_0$ .
- 5 Specify the  $\mathbf{u}_0$  vector as


|       |     |
|-------|-----|
| $u_0$ | $x$ |
| $v_0$ | $y$ |

- 6 Locate the **Fluid Properties** section. From the  $\rho_0$  list, choose **User defined**. In the associated text field, type  $\rho_0$ .


### Symmetry I

- 1 In the **Physics** toolbar, click  **Boundaries** and choose **Symmetry**.
- 2 In the **Settings** window for **Symmetry**, locate the **Boundary Selection** section.
- 3 From the **Selection** list, choose **Symmetry**.

### Domain Sources I

- 1 In the **Physics** toolbar, click  **Domains** and choose **Domain Sources**.
- 2 Select Domains 4, 5, and 7–10 only.
- 3 In the **Settings** window for **Domain Sources**, locate the **Domain Sources** section.
- 4 In the  $p_{rc}$  text field, type  $S \cdot \cos(\omega_0 \cdot t)$ .


### Specific Acoustic Impedance (Isentropic) I

- 1 In the **Physics** toolbar, click  **Boundaries** and choose **Specific Acoustic Impedance (Isentropic)**.
- 2 Select Boundaries 1, 3, 5, 7, 14, 23, and 31–34 only.

Proceed and create the mesh. Use a dense mesh resolution for the jet and source regions and a structured mesh for the PML/AL.

## MESH I

### Free Triangular I


- 1 In the **Mesh** toolbar, click  **Free Triangular**.
- 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 5, 7, 9, and 10 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  $1\text{m}0/20$ .
- 5 In the **Minimum element size** text field, type 0.1.

#### *Size 1*

- 1 In the **Model Builder** window, right-click **Free Triangular 1** and choose **Size**.
- 2 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.
- 3 Click  **Clear Selection**.
- 4 Select Domains 7 and 9 only.
- 5 Locate the **Element Size** section. Click the **Custom** button.
- 6 Locate the **Element Size Parameters** section.
- 7 Select the **Maximum element size** checkbox. In the associated text field, type 0.8.

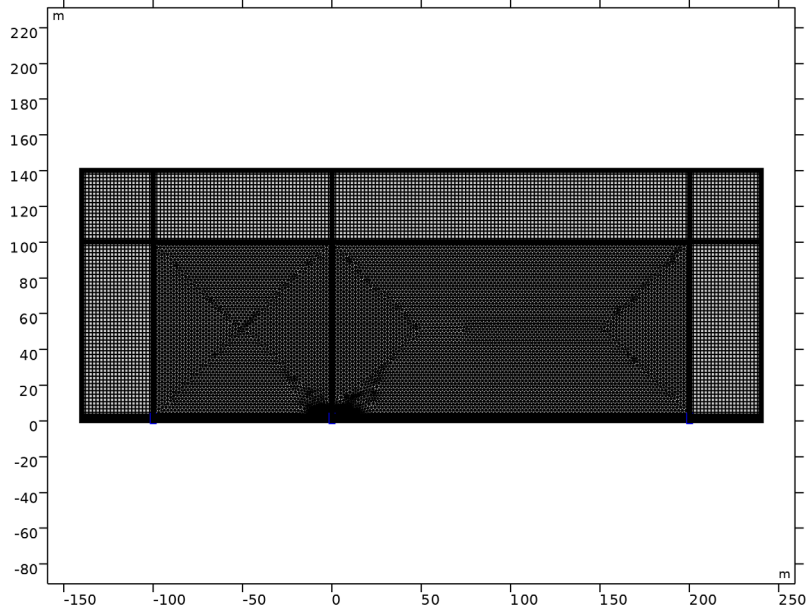
#### *Mapped 1*

- 1 In the **Mesh** toolbar, click  **Mapped**.
- 2 In the **Settings** window for **Mapped**, click to expand the **Reduce Element Skewness** section.
- 3 Select the **Adjust edge mesh** checkbox.

#### *Distribution 1*

- 1 Right-click **Mapped 1** and choose **Distribution**.
- 2 Select Boundaries 8, 16, and 25 only.

3 In the **Settings** window for **Distribution**, click  **Build All**.





Now, solve the model first in the frequency domain, then in the time domain. Once solved, proceed and analyze the results.

### 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** checkbox.

*Step 1: Frequency Domain*

- 1 In the **Study** toolbar, click  **Frequency Domain**.
- 2 In the **Settings** window for **Frequency Domain**, locate the **Study Settings** section.
- 3 In the **Frequencies** text field, type  $f_0$ .
- 4 Locate the **Physics and Variables Selection** section. Select the **Modify model configuration for study step** checkbox.
- 5 In the tree, select **Component 1 (comp1) > Definitions > Artificial Domains > Absorbing Layer 1 (ab1)**.
- 6 Click  **Disable**.
- 7 In the **Model Builder** window, click **Study 1**.

8 In the **Settings** window for **Study**, type Study 1 - Frequency Domain in the **Label** text field.

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

## ADD STUDY

1 In the **Home** toolbar, click  **Windows** and choose **Add Study**.

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

3 Find the **Physics interfaces in study** subsection. In the table, clear the **Solve** checkbox for **Linearized Euler, Frequency Domain (lef)**.

4 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies > Time Dependent**.

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

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

## STUDY 2

### *Step 1: Time Dependent*

1 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.

2 In the **Output times** text field, type range(0, Tperiod/10, Tend).

3 Locate the **Physics and Variables Selection** section. Select the **Modify model configuration for study step** checkbox.

4 In the tree, select **Component 1 (comp1) > Definitions > Artificial Domains > Perfectly Matched Layer 1 (pml1)**.


5 Click  **Disable**.

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

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

8 Clear the **Generate default plots** checkbox.

9 In the **Label** text field, type Study 2 - Time Domain.

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


## RESULTS

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

### *Study 1 - Frequency Domain/Solution 1 (sol1)*

In the **Model Builder** window, expand the **Results > Datasets** node, then click **Study 1 - Frequency Domain/Solution 1 (sol1)**.


*Selection*

- 1 In the **Results** toolbar, click  **Attributes** and choose **Selection**.
- 2 In the **Settings** window for **Selection**, locate the **Geometric Entity Selection** section.
- 3 From the **Geometric entity level** list, choose **Domain**.
- 4 Select Domains 4, 5, and 7–10 only.


*Study 2 - Time Domain/Solution 2 (sol2)*

In the **Model Builder** window, under **Results** > **Datasets** click **Study 2 - Time Domain/Solution 2 (sol2)**.


*Selection*

- 1 In the **Results** toolbar, click  **Attributes** and choose **Selection**.
- 2 In the **Settings** window for **Selection**, locate the **Geometric Entity Selection** section.
- 3 From the **Geometric entity level** list, choose **Domain**.
- 4 Select Domains 4, 5, and 7–10 only.


*Mirror 2D - Frequency Domain*

- 1 In the **Results** toolbar, click  **More Datasets** and choose **Mirror 2D**.
- 2 In the **Settings** window for **Mirror 2D**, locate the **Axis Data** section.
- 3 In row **Point 2**, set **X** to 1.
- 4 In row **Point 2**, set **Y** to 0.
- 5 In the **Label** text field, type Mirror 2D - Frequency Domain.

*Mirror 2D - Time Domain*


- 1 In the **Results** toolbar, click  **More Datasets** and choose **Mirror 2D**.
- 2 In the **Settings** window for **Mirror 2D**, locate the **Data** section.
- 3 From the **Dataset** list, choose **Study 2 - Time Domain/Solution 2 (sol2)**.
- 4 Locate the **Axis Data** section. In row **Point 2**, set **X** to 1.
- 5 In row **Point 2**, set **Y** to 0.
- 6 In the **Label** text field, type Mirror 2D - Time Domain.

*Cut Line 2D -  $y=15$ , Frequency Domain*


- 1 In the **Results** toolbar, click  **Cut Line 2D**.
- 2 In the **Settings** window for **Cut Line 2D**, type Cut Line 2D -  $y=15$ , Frequency Domain in the **Label** text field.
- 3 Locate the **Line Data** section. In row **Point 1**, set **X** to  $X_{min}$ .

- 4 In row **Point 1**, set **Y** to 15.
- 5 In row **Point 2**, set **X** to Xmax.
- 6 In row **Point 2**, set **Y** to 15.


*Cut Line 2D -  $y=15$ , Time Domain*

- 1 In the **Results** toolbar, click  **Cut Line 2D**.
- 2 In the **Settings** window for **Cut Line 2D**, type Cut Line 2D -  $y=15$ , Time Domain in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Study 2 - Time Domain/ Solution 2 (sol2)**.
- 4 Locate the **Line Data** section. In row **Point 1**, set **X** to Xmin.
- 5 In row **Point 1**, set **Y** to 15.
- 6 In row **Point 2**, set **X** to Xmax.
- 7 In row **Point 2**, set **Y** to 15.

*Cut Line 2D - Analytical*


- 1 In the **Results** toolbar, click  **Cut Line 2D**.
- 2 In the **Settings** window for **Cut Line 2D**, type Cut Line 2D - Analytical in the **Label** text field.
- 3 Locate the **Line Data** section. In row **Point 1**, set **X** to -50.
- 4 In row **Point 1**, set **Y** to 15.
- 5 In row **Point 2**, set **X** to 150.
- 6 In row **Point 2**, set **Y** to 15.

*Pressure (lef)*

- 1 In the **Results** toolbar, click  **2D Plot Group**.
- 2 In the **Settings** window for **2D Plot Group**, type Pressure (lef) in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Mirror 2D - Frequency Domain**.
- 4 Locate the **Color Legend** section. Select the **Show units** checkbox.

*Surface 1*

- 1 Right-click **Pressure (lef)** and choose **Surface**.
- 2 In the **Settings** window for **Surface**, locate the **Expression** section.
- 3 In the **Expression** text field, type  $lef.p\_t$ .
- 4 Locate the **Coloring and Style** section. From the **Color table** list, choose **Wave**.
- 5 From the **Scale** list, choose **Linear symmetric**.

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

*Height Expression 1*

Right-click **Surface 1** and choose **Height Expression**.

*Contour 1*

**1** In the **Model Builder** window, right-click **Pressure (lef)** and choose **Contour**.

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

**3** In the **Expression** text field, type `lef.p_t`.

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

**5** From the **Scale** list, choose **Linear symmetric**.

**6** Clear the **Color legend** checkbox.

*Height Expression 1*


**1** Right-click **Contour 1** and choose **Height Expression**.

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

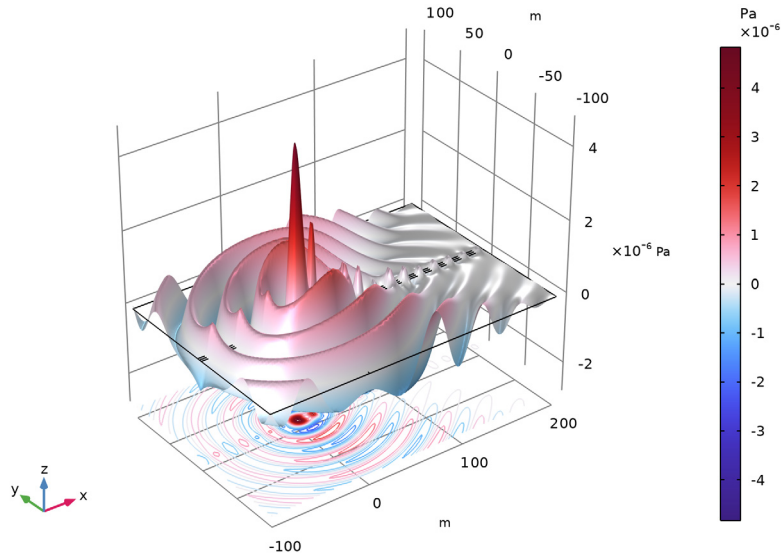
**3** Select the **Scale factor** checkbox. In the associated text field, type `1`.

**4** In the **Offset** text field, type `-100`.


**5** Clear the **Show height axis** checkbox.

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

freq(1)=12.096 Hz Surface: Total acoustic pressure (Pa) Contour: Total acoustic pressure (Pa)




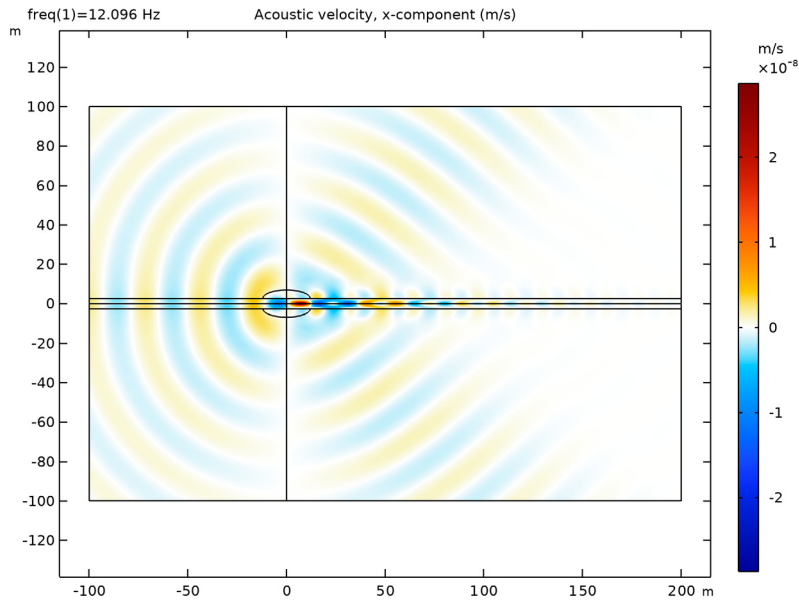
*x-velocity (lef)*

- 1 In the **Results** toolbar, click  **2D Plot Group**.
- 2 In the **Settings** window for **2D Plot Group**, type *x-velocity (lef)* in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Mirror 2D - Frequency Domain**.
- 4 Locate the **Color Legend** section. Select the **Show units** checkbox.


*Surface 1*

- 1 Right-click **x-velocity (lef)** and choose **Surface**.
- 2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1) > Linearized Euler, Frequency Domain > Acoustic fields > Acoustic velocity - m/s > u - Acoustic velocity, x-component**.
- 3 Locate the **Coloring and Style** section. From the **Color table** list, choose **Ranitomeya**.
- 4 From the **Scale** list, choose **Linear symmetric**.
- 5 From the **Color table transformation** list, choose **Nonlinear symmetric**.
- 6 In the **Color calibration parameter** text field, type -1.

7 In the **x-velocity (lef)** toolbar, click  **Plot**.



*y-velocity (lef)*

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

2 In the **Settings** window for **2D Plot Group**, type *y-velocity (lef)* in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Mirror 2D - Frequency Domain**.

4 Locate the **Color Legend** section. Select the **Show units** checkbox.

*Surface 1*


1 Right-click **y-velocity (lef)** and choose **Surface**.

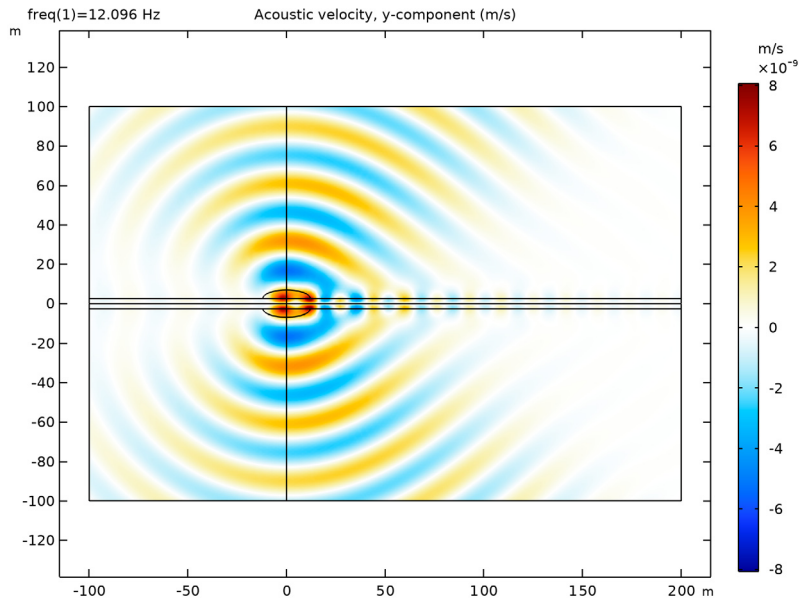
2 In the **Settings** window for **Surface**, locate the **Expression** section.

3 In the **Expression** text field, type *v*.


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

5 From the **Scale** list, choose **Linear symmetric**.

6 In the **y-velocity (lef)** toolbar, click  **Plot**.



*Real(p) at  $y = 0$  and  $y = 15$  (frequency)*

- 1 In the **Results** toolbar, click  **ID Plot Group**.
- 2 In the **Settings** window for **ID Plot Group**, type **Real(p) at  $y = 0$  and  $y = 15$  (frequency)** in the **Label** text field.
- 3 Click to expand the **Title** section. From the **Title type** list, choose **Label**.

*Line Graph 1*

- 1 Right-click **Real(p) at  $y = 0$  and  $y = 15$  (frequency)** and choose **Line Graph**.
- 2 In the **Settings** window for **Line Graph**, locate the **Data** section.
- 3 From the **Dataset** list, choose **Cut Line 2D -  $y=15$ , Frequency Domain**.
- 4 Locate the **y-Axis Data** section. In the **Expression** text field, type **lef.p\_t**.
- 5 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.
- 6 In the **Expression** text field, type **x**.
- 7 Click to expand the **Legends** section. Select the **Show legends** checkbox.
- 8 From the **Legends** list, choose **Manual**.

9 In the table, enter the following settings:

---

**Legends**

Pressure at  $y = 15$  m

---

*Line Graph 2*


- 1 In the **Model Builder** window, right-click **Real(p) at  $y = 0$  and  $y = 15$  (frequency)** and choose **Line Graph**.
- 2 In the **Settings** window for **Line Graph**, locate the **Selection** section.
- 3 Click to select the  **Activate Selection** toggle button.
- 4 Select Boundaries 9 and 17 only.
- 5 Locate the **y-Axis Data** section. In the **Expression** text field, type  $1e^f \cdot p_t$ .
- 6 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.
- 7 In the **Expression** text field, type  $x$ .
- 8 Click to expand the **Legends** section. Select the **Show legends** checkbox.
- 9 From the **Legends** list, choose **Manual**.
- 10 In the table, enter the following settings:

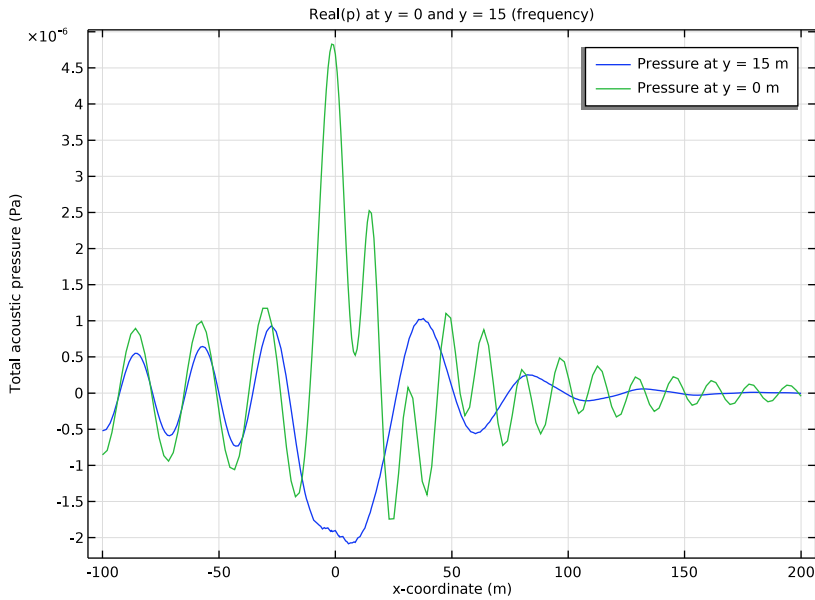
---

**Legends**


Pressure at  $y = 0$  m

---

II In the **Real(p) at y = 0 and y = 15 (frequency)** toolbar, click  **Plot**.



*Real(p) at y = 15 (frequency)*

- 1 In the **Results** toolbar, click  **ID Plot Group**.
- 2 In the **Settings** window for **ID Plot Group**, type **Real(p) at y = 15 (frequency)** in the **Label** text field.
- 3 Click to expand the **Title** section. From the **Title type** list, choose **Label**.
- 4 Locate the **Data** section. From the **Dataset** list, choose **Cut Line 2D - y=15, Frequency Domain**.
- 5 Locate the **Plot Settings** section.
- 6 Select the **x-axis label** checkbox. In the associated text field, type **x (m)**.
- 7 Select the **y-axis label** checkbox. In the associated text field, type **Pressure (Pa)**.

*Line Graph 1*

- 1 Right-click **Real(p) at y = 15 (frequency)** and choose **Line Graph**.
- 2 In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.
- 3 In the **Expression** text field, type **lef.p\_t**.
- 4 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.
- 5 In the **Expression** text field, type **x**.

- 6 Click to expand the **Legends** section. Select the **Show legends** checkbox.
- 7 From the **Legends** list, choose **Manual**.
- 8 In the table, enter the following settings:

| <b>Legends</b> |
|----------------|
| Model          |

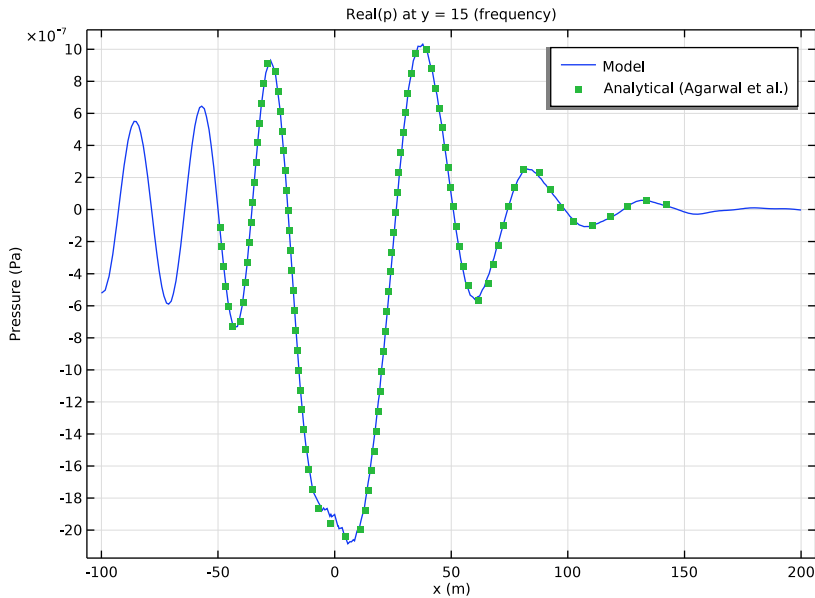
*Line Graph 2*

- 1 In the **Model Builder** window, right-click **Real(p) at y = 15 (frequency)** and choose **Line Graph**.
- 2 In the **Settings** window for **Line Graph**, locate the **Data** section.
- 3 From the **Dataset** list, choose **Cut Line 2D - Analytical**.
- 4 Locate the **y-Axis Data** section. In the **Expression** text field, type `int_p_real(x)`.
- 5 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.
- 6 In the **Expression** text field, type `x`.
- 7 Click to expand the **Legends** section. Select the **Show legends** checkbox.
- 8 From the **Legends** list, choose **Manual**.
- 9 In the table, enter the following settings:

| <b>Legends</b>              |
|-----------------------------|
| Analytical (Agarwal et al.) |

- 10 Click to expand the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **None**.
- 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 100.

14 In the **Real(p) at y = 15 (frequency)** toolbar, click  **Plot**.



*Imag(p) at y = 15 (frequency)*

- 1 Right-click **Real(p) at y = 15 (frequency)** and choose **Duplicate**.
- 2 In the **Settings** window for **ID Plot Group**, type **Imag(p) at y = 15 (frequency)** in the **Label** text field.
- 3 Click to expand the **Title** section. From the **Title type** list, choose **Label**.

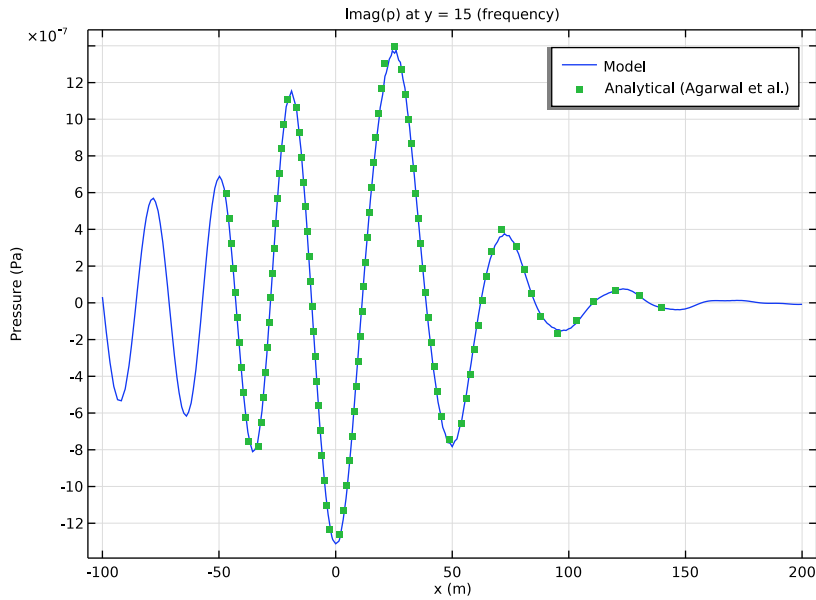
*Line Graph 1*

- 1 In the **Model Builder** window, expand the **Imag(p) at y = 15 (frequency)** node, then click **Line Graph 1**.
- 2 In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.
- 3 In the **Expression** text field, type `imag(1ef.p_t)`.


*Line Graph 2*

- 1 In the **Model Builder** window, click **Line Graph 2**.
- 2 In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.
- 3 In the **Expression** text field, type `int_p_imag(x)`.


4 In the **Imag(p) at y = 15 (frequency)** toolbar, click  **Plot**.



*Pressure (let)*


- 1 In the **Results** toolbar, click  **2D Plot Group**.
- 2 In the **Settings** window for **2D Plot Group**, type **Pressure (let)** in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Mirror 2D - Time Domain**.
- 4 Locate the **Color Legend** section. Select the **Show units** checkbox.
- 5 Locate the **Data** section. From the **Time (s)** list, choose **0.53738**.

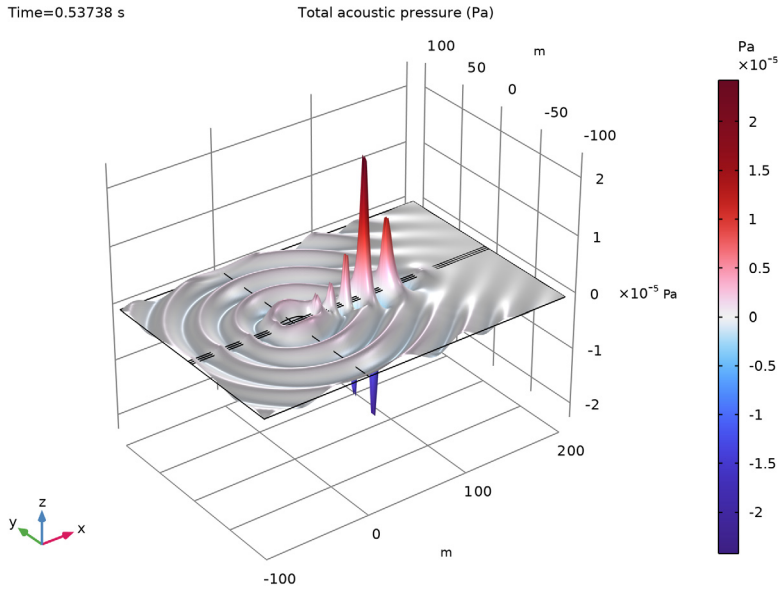
*Surface I*

- 1 Right-click **Pressure (let)** and choose **Surface**.
- 2 In the **Settings** window for **Surface**, locate the **Expression** section.
- 3 In the **Expression** text field, type `let .p_t`.
- 4 Locate the **Coloring and Style** section. From the **Color table** list, choose **Wave**.
- 5 From the **Scale** list, choose **Linear symmetric**.
- 6 In the **Pressure (let)** toolbar, click  **Plot**.


*Height Expression I*

- 1 In the **Model Builder** window, right-click **Surface I** and choose **Height Expression**.

- 2 In the **Pressure (let)** toolbar, click  **Plot**.



*Comparison at  $y = 15$  (time and frequency)*


- 1 In the **Results** toolbar, click  **ID Plot Group**.
- 2 In the **Settings** window for **ID Plot Group**, type Comparison at  $y = 15$  (time and frequency) 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** checkbox. In the associated text field, type  $x$  (m).
- 7 Select the **y-axis label** checkbox. In the associated text field, type Pressure (Pa).

*Line Graph 1*

- 1 Right-click **Comparison at  $y = 15$  (time and frequency)** and choose **Line Graph**.
- 2 In the **Settings** window for **Line Graph**, locate the **Data** section.
- 3 From the **Dataset** list, choose **Cut Line 2D -  $y=15$ , Frequency Domain**.
- 4 Locate the **y-Axis Data** section. In the **Expression** text field, type  $1ef.p\_t$ .
- 5 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.
- 6 In the **Expression** text field, type  $x$ .

- 7 Click to expand the **Legends** section. Select the **Show legends** checkbox.
- 8 From the **Legends** list, choose **Manual**.
- 9 In the table, enter the following settings:


| <b>Legends</b>   |
|------------------|
| Frequency domain |

- 10 In the **Comparison at  $y = 15$  (time and frequency)** toolbar, click  **Plot**.

#### *Line Graph 2*

- 1 In the **Model Builder** window, right-click **Comparison at  $y = 15$  (time and frequency)** and choose **Line Graph**.
- 2 In the **Settings** window for **Line Graph**, locate the **Data** section.
- 3 From the **Dataset** list, choose **Cut Line 2D -  $y=15$ , Time Domain**.
- 4 From the **Time selection** list, choose **Last**.
- 5 Locate the **y-Axis Data** section. In the **Expression** text field, type `let.p_t`.
- 6 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.
- 7 In the **Expression** text field, type `x`.
- 8 Click to expand the **Legends** section. Select the **Show legends** checkbox.
- 9 From the **Legends** list, choose **Manual**.
- 10 In the table, enter the following settings:

| <b>Legends</b> |
|----------------|
| Time domain    |

- 11 In the **Comparison at  $y = 15$  (time and frequency)** toolbar, click  **Plot**.

#### *Line Graph 3*

- 1 Right-click **Comparison at  $y = 15$  (time and frequency)** and choose **Line Graph**.
- 2 In the **Settings** window for **Line Graph**, locate the **Data** section.
- 3 From the **Dataset** list, choose **Cut Line 2D - Analytical**.
- 4 Locate the **y-Axis Data** section. In the **Expression** text field, type `int_p_real(x)`.
- 5 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.
- 6 In the **Expression** text field, type `x`.
- 7 Click to expand the **Legends** section. Select the **Show legends** checkbox.
- 8 From the **Legends** list, choose **Manual**.

9 In the table, enter the following settings:

---

**Legends**

---

Analytical (Agarwal et al.)


---

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

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 100.

14 In the **Comparison at  $y = 15$  (time and frequency)** toolbar, click  **Plot**.

*Comparison at  $y = 15$  (time and frequency)*

1 In the **Model Builder** window, click **Comparison at  $y = 15$  (time and frequency)**.

2 In the **Settings** window for **ID Plot Group**, locate the **Axis** section.


3 Select the **Manual axis limits** checkbox.

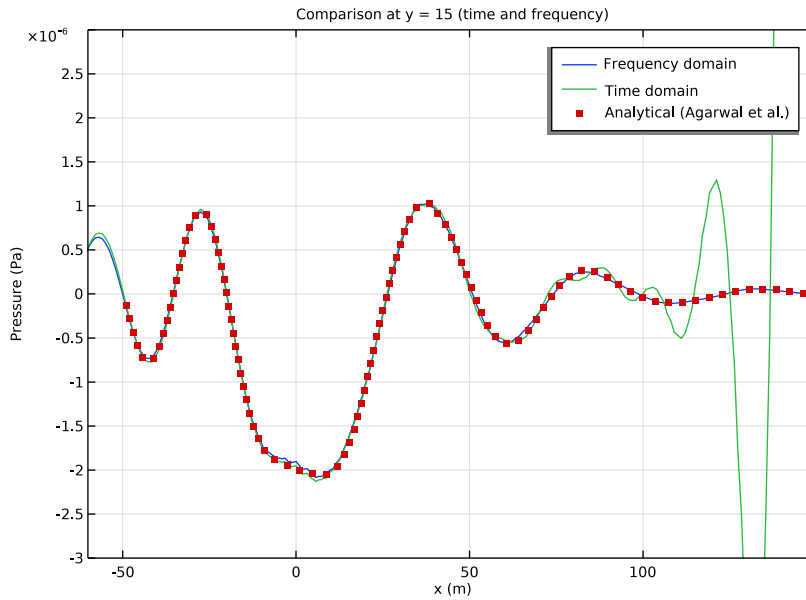
4 In the **x minimum** text field, type -60.

5 In the **x maximum** text field, type 150.


6 In the **y minimum** text field, type  $-3e-6$ .

7 In the **y maximum** text field, type  $3e-6$ .


8 In the **Comparison at y = 15 (time and frequency)** toolbar, click  **Plot**.



*Comparison at x = 0 (time and frequency)*

- 1 In the **Results** toolbar, click  **ID Plot Group**.
- 2 In the **Settings** window for **ID Plot Group**, type Comparison at x = 0 (time and frequency) in the **Label** text field.
- 3 Click to expand the **Title** section. From the **Title type** list, choose **Label**.
- 4 Locate the **Plot Settings** section.
- 5 Select the **x-axis label** checkbox. In the associated text field, type y (m).
- 6 Select the **y-axis label** checkbox. In the associated text field, type Pressure (Pa).

*Line Graph 1*

- 1 Right-click **Comparison at x = 0 (time and frequency)** and choose **Line Graph**.
- 2 In the **Settings** window for **Line Graph**, locate the **Selection** section.
- 3 Click to select the  **Activate Selection** toggle button.
- 4 Select Boundaries 16, 18, and 20 only.
- 5 Locate the **y-Axis Data** section. In the **Expression** text field, type  $1e6 \cdot p_t$ .
- 6 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.
- 7 In the **Expression** text field, type y.

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

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

10 In the table, enter the following settings:

---

| <b>Legends</b>   |
|------------------|
| Frequency domain |

*Line Graph 2*

1 In the **Model Builder** window, right-click **Comparison at  $x = 0$  (time and frequency)** and choose **Line Graph**.

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

3 From the **Dataset** list, choose **Study 2 - Time Domain/Solution 2 (sol2)**.

4 From the **Time selection** list, choose **Last**.

5 Select Boundaries 16, 18, and 20 only.

6 Locate the **y-Axis Data** section. In the **Expression** text field, type `1et.p_t`.

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

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

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

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

11 In the table, enter the following settings:

---

| <b>Legends</b> |
|----------------|
| Time domain    |

12 In the **Comparison at x = 0 (time and frequency)** toolbar, click  **Plot**.

