Lumped Loudspeaker Driver Transient Analysis with Nonlinear Large-Signal Parameters

Introduction

This model shows how to include the nonlinear (large signal) behavior of certain lumped components in a simplified loudspeaker analysis in the time domain. The mechanical and electrical system is modeled using an equivalent electrical circuit (a Thiele–Small representation). The large signal compliance $C_{MS}(x)$ and force factor $BL(x)$ are here nonlinear functions of the speaker location. Moreover, the mechanical damping $R_{MS}(v)$ is a function of the speaker velocity.

The nonlinear effects associated with the compliance and BL factor are especially important at lower frequencies. This is also where a lumped modeling approach of the electromechanical system has its main application. At higher frequencies the piston assumption, of the lumped model, is no longer valid and breakup can occur in the membrane and other mechanical components. The approach is in particular relevant for microtransducer modeling (and their implementation in larger system designs) as the lumped representation is valid in a larger frequency range, due to the small size.

The model uses the built-in coupling between the **Interior Lumped Speaker Boundary** (or **Lumped Speaker Boundary**, if the back volume is also lumped) feature in the **Pressure Acoustics, Transient** interface and an **Electrical Circuit** interface. The axial speaker location x and speaker membrane velocity v exist as predefined built-in variables.

Model Definition

The model definitions, geometry, and most details of the lumped model follow the setup in the frequency domain variant; the Lumped Loudspeaker Driver also found in the Acoustics Module Application Library. In the present model, only the open back volume configuration is modeled.

This model is solved in the time domain which changes the allowed structure of the circuit. All values of the components need to be real valued and cannot be a function of frequency. This limits the possibility to, for example, use frequency dependent component values to model certain loss types. The components values can, on the other hand, be given by time dependent quantities which allows the introduction of the large signal values: compliance $C_{MS}(x)$, force factor $BL(x)$, and the mechanical damping $R_{MS}(v)$, where the time dependency is through $x = x(t)$ and $v = v(t)$. The axial location of the diaphragm (the mechanical system) x is defined through a predefined (global) variable `actd.ilsb1.x_ax` and the diaphragm velocity v is defined through a predefined (global) variable `actd.ilsb1.v_ax`. When using these, add the appropriate physics and feature tags.

The large signal parameters are depicted in Figure 1. The values of the curves are taken to roughly correspond to properties extracted from the Loudspeaker Driver — Frequency-Domain Analysis and the Loudspeaker Driver — Transient Analysis tutorial models. The data is just an example for the purpose of demonstration in this model.

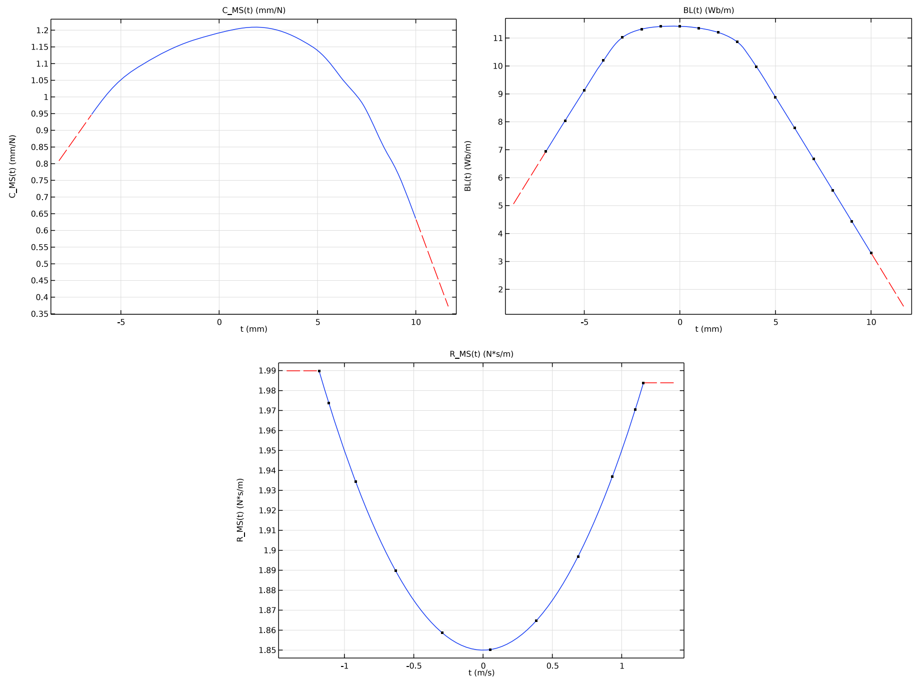


Figure 1: Large signal parameters used in the model, $C_{MS}(x)$, $BL(x)$, and $R_{MS}(v)$.

In this model, the applied voltage (to the Voltage Source in the Electrical Circuit model) is a single frequency harmonic signal of the type

$$V(t) = V_0 \sin(2\pi f_0 t)$$

where the frequency f_0 is set to 50 Hz and the signal amplitude V_0 is 15 V. Both values can be found in the Parameters list and modified as necessary. The current input signal will allow for the evaluation of the total harmonic distortion (THD); the signal can be modified to any desired signal, for example, if inter modulation distortion (IMD) is of interest. Note that in the model a ramp is added to the signal to increase it smoothly over the first period. In the analysis of the results, the first two periods are skipped in order to avoid inclusion of any transients.

Results and Discussion

The model contains several plots that analyze the response of the speaker as well as the behavior and contribution of the large signal parameters. The contribution of each large signal parameter, to the overall nonlinear behavior of the speaker, can of course be studied by setting one or more of the parameters to constants.

The pressure is evaluated in a point 20 cm in front of the speaker. The time signal is depicted in Figure 2. The frequency spectrum of the nonlinear periodic part of the signal (skipping the first two periods) is depicted in Figure 3. The peak values of the generated harmonics are also depicted. These can be used to evaluate the THD.

The speaker axial position and velocity as function of time are depicted in Figure 4. Finally, the variation of the large signal parameters over time is depicted in Figure 5.

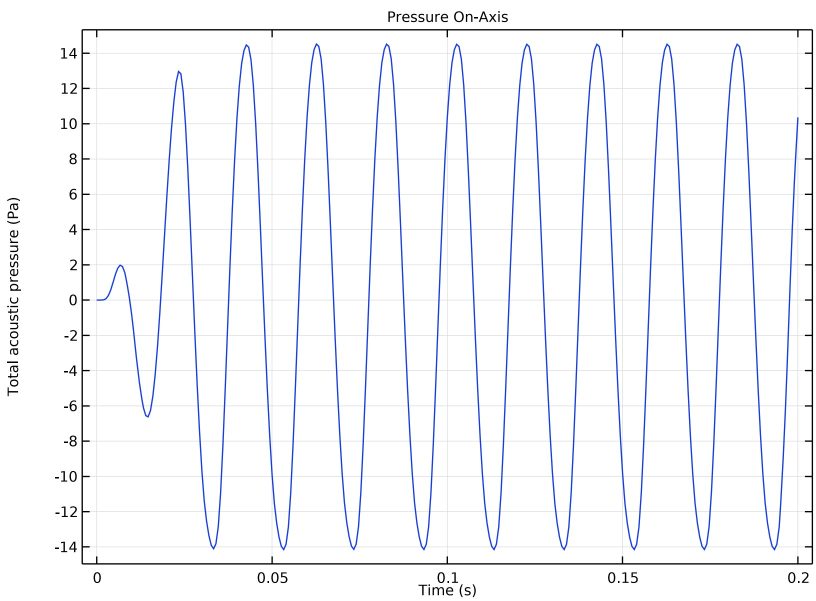


Figure 2: Pressure as function of time.

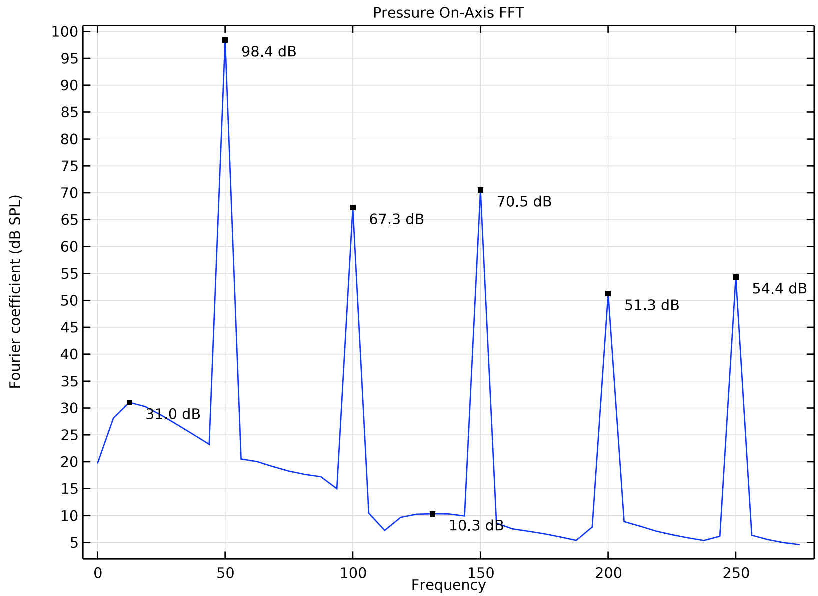


Figure 3: Frequency spectrum of the nonlinear periodic part of the signal. Peak values shown for the generated harmonics.

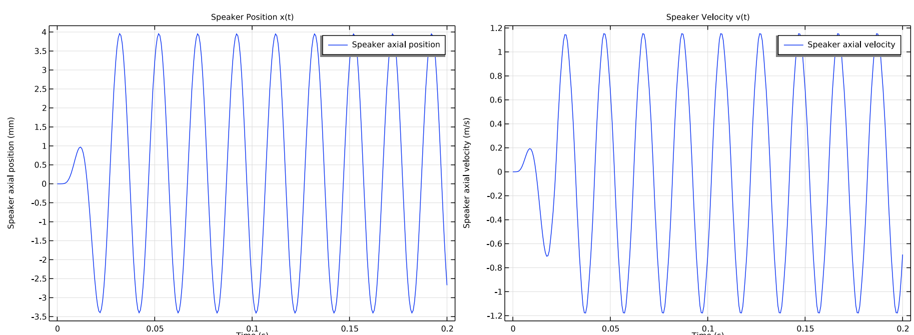


Figure 4: Axial position and velocity as function of time.

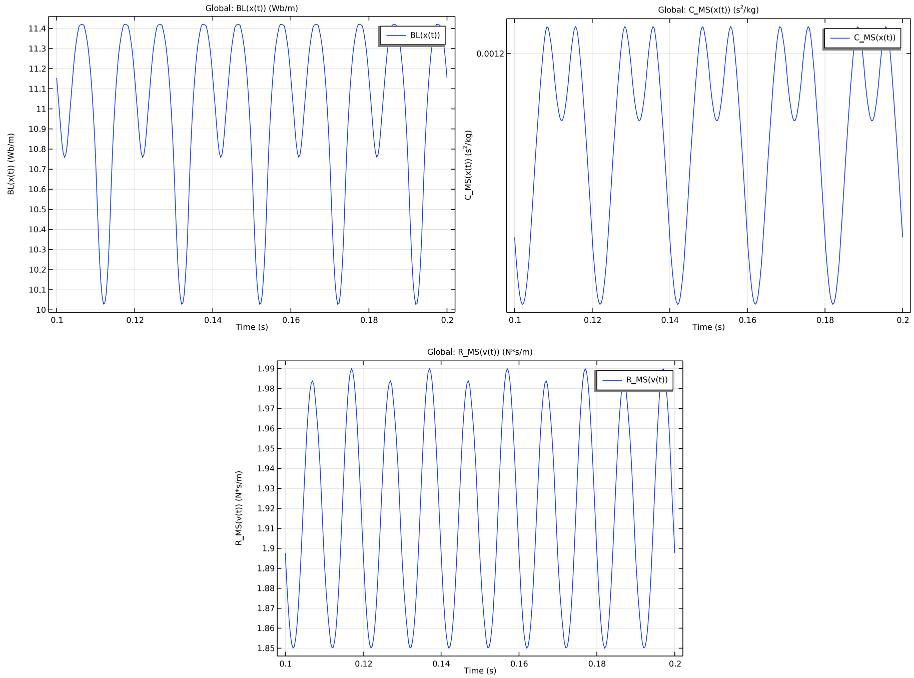


Figure 5: The variation of the large signal parameters as function of time.

Notes About The COMSOL Implementation

In the **Electrical Circuit** interface the capacitor in the mechanical system (representing the compliance of the suspension) is modeled using a **Voltage-Controlled Current Source** device. This is in order to ensure that the time varying capacitance (the compliance) is taken fully into account. The compliance is time dependent in the model through the displacement: $\mathrm{C_{MS}} = \mathrm{C_{MS}(x)} = \mathrm{C_{MS}}(x(\mathrm{t}))$. The setup ensures that the current-voltage relation for the device follows

$$I = \frac{dQ}{dt} = \frac{d}{dt}(C_{\mathrm{MS}}(t)V) \tag{1}$$

such that the full time derivative is taken (chain-rule is automatically applied). Here, Q is the charge. The built-in capacitor device uses the simpler relation

$$I = C_{\mathrm{MS}}(t)\frac{dV}{dt}\,. \tag{2}$$

Application Library path: `Acoustics_Module/Electroacoustic_Transducers/lumped_loudspeaker_driver_transient`

Modeling Instructions

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

NEW

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

MODEL WIZARD

1 In the **Model Wizard** window, click **2D Axisymmetric**.

2 In the **Select Physics** tree, select **Acoustics>Pressure Acoustics>Pressure Acoustics, Transient (actd)**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **General Studies>Time Dependent**.

6 Click **Done**.

GLOBAL DEFINITIONS

Parameters 1

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

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

3 Click **Load from File**.

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

Interpolation 1 (int1)

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

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

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

4 Click **Browse**.

5 Browse to the model's Application Libraries folder and double-click the file `lumped_loudspeaker_driver_transient_bl.txt`.

6 Click **Import**.

7 In the **Function name** text field, type `BL`.

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

9 From the **Extrapolation** list, choose **Linear**.

10 Locate the **Units** section. In the **Function** table, enter the following settings:

Function	Unit
BL	Wb/m

11 In the **Argument** table, enter the following settings:

Argument	Unit
t	mm

Interpolation 2 (int2)

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

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

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

4 Click **Browse**.

5 Browse to the model's Application Libraries folder and double-click the file `lumped_loudspeaker_driver_transient_c_ms.txt`.

6 Click **Import**.

7 In the **Function name** text field, type `C_MS`.

8 Locate the **Interpolation and Extrapolation** section. From the **Extrapolation** list, choose **Linear**.

9 Locate the **Units** section. In the **Function** table, enter the following settings:

Function	Unit
C_MS	mm/N

10 In the **Argument** table, enter the following settings:

Argument	Unit
t	mm

Interpolation 3 (int3)

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

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

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

4 Click **Browse**.

5 Browse to the model's Application Libraries folder and double-click the file `lumped_loudspeaker_driver_transient_r_ms.txt`.

6 Click **Import**.

7 In the **Function name** text field, type `R_MS`.

8 Locate the **Interpolation and Extrapolation** section. From the **Interpolation** list, choose **Cubic spline**.

9 Locate the **Units** section. In the **Function** table, enter the following settings:

Function	Unit
R_MS	`N*s/m`

10 In the **Argument** table, enter the following settings:

Argument	Unit
t	`m/s`

DEFINITIONS

Ramp 1 (rm1)

1 In the **Home** toolbar, click f(X) **Functions** and choose **Local>Ramp**.

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

3 In the **Location** text field, type `0.1*T0`.

4 In the **Slope** text field, type `1/T0`.

5 Select the **Cutoff** check box.

6 Click to expand the **Smoothing** section.

7 Select the **Size of transition zone at start** check box. In the associated text field, type `0.2*T0`.

8 Select the **Size of transition zone at cutoff** check box. In the associated text field, type `0.2*T0`.

GEOMETRY 1

Circle 1 (c1)

1 In the **Geometry** toolbar, click **Circle**.
2 In the **Settings** window for **Circle**, locate the **Size and Shape** section.
3 In the **Radius** text field, type `1[cm]`.
4 In the **Sector angle** text field, type `180`.
5 Locate the **Position** section. In the **r** text field, type `a`.

Circle 2 (c2)

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 `Rair+Rpml`.
4 In the **Sector angle** text field, type `180`.
5 Locate the **Rotation Angle** section. In the **Rotation** text field, type `-90`.
6 Click to expand the **Layers** section. In the table, enter the following settings:

Layer name	Thickness (m)
Layer 1	Rpml

Polygon 1 (pol1)

1 In the **Geometry** toolbar, click **Polygon**.
2 In the **Settings** window for **Polygon**, locate the **Object Type** section.
3 From the **Type** list, choose **Open curve**.
4 Locate the **Coordinates** section. In the table, enter the following settings:

r (m)	z (m)
3[cm]	-4[cm]
a-1[cm]	0

Polygon 2 (pol2)

1 In the **Geometry** toolbar, click **Polygon**.
2 In the **Settings** window for **Polygon**, locate the **Object Type** section.
3 From the **Type** list, choose **Open curve**.

4 Locate the **Coordinates** section. In the table, enter the following settings:

r (m)	z (m)
a+1[cm]	0
Rair	0

5 Click **Build All Objects**.

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

Quadratic Bézier 1 (qb1)

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

2 In the **Settings** window for **Quadratic Bézier**, locate the **Control Points** section.

3 In row **2**, set **r** to 1.8[cm].

4 In row **3**, set **r** to 3[cm].

5 In row **1**, set **z** to -3[cm].

6 In row **2**, set **z** to -3.1[cm].

7 In row **3**, set **z** to -4[cm].

8 Locate the **Weights** section. In the **2** text field, type 1.5.

9 Click **Build All Objects**.

Delete Entities 1 (del1)

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

2 On the object **c1**, select Boundaries 3 and 4 only.

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

Polygon 3 (pol3)

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

2 In the **Settings** window for **Polygon**, locate the **Object Type** section.

3 From the **Type** list, choose **Open curve**.

4 Locate the **Coordinates** section. In the table, enter the following settings:

r (m)	z (m)
0.15	0
0.15	-0.1
0	-0.1

5 Click **Build All Objects**.

DEFINITIONS

Perfectly Matched Layer 1 (pml1)

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

2 Select Domains 1 and 5 only.

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

4 In the **PML scaling curvature parameter** text field, type `3`.

Baffle (interior wall)

1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, type `Baffle (interior wall)` in the **Label** text field.

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

4 Select Boundaries 9, 11, 12, and 19 only.

Speaker

1 In the **Definitions** toolbar, click **Explicit**.

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

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

4 Select Boundaries 8, 15, and 18 only.

PRESSURE ACOUSTICS, TRANSIENT (ACTD)

Interior Sound Hard Boundary (Wall) 1

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Pressure Acoustics, Transient (actd)** and choose **Interior Conditions>Interior Sound Hard Boundary (Wall)**.

2 In the **Settings** window for **Interior Sound Hard Boundary (Wall)**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Baffle (interior wall)**.

Interior Lumped Speaker Boundary 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Interior Lumped Speaker Boundary**.

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

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

Proceed and add the electric circuit model for the speaker (the Thiele-Small representation). For the lumped mechanical part of the model, the units will be transformed from mechanical to electric; this is only to avoid the unit warning, the model solves nicely without the unit transform.

It is in the lumped model that the nonlinear parameters are used. The **Interior Lumped Speaker Boundary** defines variables for the axial position and the axial velocity; they are `actd.ilsb1.x_ax` and `actd.ilsb1.v_ax`, respectively.

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 **AC/DC>Electrical Circuit (cir)**.

4 Click **Add to Component 1** in the window toolbar.

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

ELECTRICAL CIRCUIT (CIR)

Voltage Source 1 (V1)

1 Right-click **Component 1 (comp1)>Electrical Circuit (cir)** and choose **Voltage Source**.

2 In the **Settings** window for **Voltage Source**, locate the **Node Connections** section.

3 In the table, enter the following settings:

Label	Node names
n	0

4 Locate the **Device Parameters** section. In the v_{src} text field, type `V0*sin(2*pi*f0*t)*nojac(rm1(t))`.

Resistor 1 (R1)

1 In the **Electrical Circuit** toolbar, click **Resistor**.

2 In the **Settings** window for **Resistor**, locate the **Node Connections** section.

3 In the table, enter the following settings:

Label	Node names
p	1
n	2

4 Locate the **Device Parameters** section. In the R text field, type `R_E`.

Inductor 1 (L1)

1 In the **Electrical Circuit** toolbar, click **Inductor**.

2 In the **Settings** window for **Inductor**, locate the **Node Connections** section.

3 In the table, enter the following settings:

Label	Node names
p	2
n	3

4 Locate the **Device Parameters** section. In the L text field, type `L_E`.

Current-Controlled Voltage Source 1 (H1)

1 In the **Electrical Circuit** toolbar, click **Current-Controlled Voltage Source**.

2 In the **Settings** window for **Current-Controlled Voltage Source**, locate the **Node Connections** section.

3 In the table, enter the following settings:

Label	Node names
p	3
n	0

4 Locate the **Device Parameters** section. In the **Gain** text field, type `BL(actd.ilsb1.x_ax)[m/Wb*ohm]`.

Current-Controlled Voltage Source 2 (H2)

1 In the **Electrical Circuit** toolbar, click **Current-Controlled Voltage Source**.

2 In the **Settings** window for **Current-Controlled Voltage Source**, locate the **Node Connections** section.

3 In the table, enter the following settings:

Label	Node names
n	0

4 Locate the **Current Measurement** section. From the **Measure current for device** list, choose **Resistor 1 (R1)**.

5 Locate the **Device Parameters** section. In the **Gain** text field, type `BL(actd.ilsb1.x_ax)[m/Wb*ohm]`.

Inductor 2 (L2)

1. In the **Electrical Circuit** toolbar, click **Inductor**.
2. In the **Settings** window for **Inductor**, locate the **Node Connections** section.
3. In the table, enter the following settings:

Label	Node names
p	4
n	5

4. Locate the **Device Parameters** section. In the L text field, type `M_MD[H/kg]`.

Current-Controlled Voltage Source 1 (H1)

1. In the **Model Builder** window, click **Current-Controlled Voltage Source 1 (H1)**.
2. In the **Settings** window for **Current-Controlled Voltage Source**, locate the **Current Measurement** section.
3. From the **Measure current for device** list, choose **Inductor 2 (L2)**.

Resistor 2 (R2)

1. In the **Electrical Circuit** toolbar, click **Resistor**.
2. In the **Settings** window for **Resistor**, locate the **Node Connections** section.
3. In the table, enter the following settings:

Label	Node names
p	5
n	6

4. Locate the **Device Parameters** section. In the R text field, type `R_MS(actd.ilsb1.v_ax)[ohm/kg*s]`.

   Next set up a voltage controlled current source in order to define a generalized capacitor, where the capacitance (the compliance of the speaker) can be time dependent. The compliance depends on position x, which depends on time t. This element will use the full time derivative, including chain-rule terms. See details in the main documentation. The effect of not including chain-rule terms can best be seen in this model by only retaining Cms(x) as large signal parameter.

Voltage-Controlled Current Source 1 - Generalized Capacitor

1. In the **Electrical Circuit** toolbar, click **Voltage-Controlled Current Source**.
2. In the **Settings** window for **Voltage-Controlled Current Source**, type `Voltage-Controlled Current Source 1 - Generalized Capacitor` in the **Label** text field.

3 Locate the **Node Connections** section. In the table, enter the following settings:

Label	Node names
p	6
n	7
measure (+)	6
measure (-)	7

4 Locate the **Device Parameters** section. From the **Method** list, choose **Custom expression**.

5 In the *isrc*(*t*,*sens.v*) text field, type `d(C_MS(actd.ilsb1.x_ax)*sens.v,t)`.

External I vs. U 1 (IvsU1)

1 In the **Electrical Circuit** toolbar, click **External I vs. U**.

2 In the **Settings** window for **External I vs. U**, locate the **Node Connections** section.

3 In the table, enter the following settings:

Label	Node names
p	7
n	0

4 Locate the **External Device** section. From the *V* list, choose **Voltage from lumped speaker boundary (actd/ilsb1)**.

PRESSURE ACOUSTICS, TRANSIENT (ACTD)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Pressure Acoustics, Transient (actd)**.

2 In the **Settings** window for **Pressure Acoustics, Transient**, locate the **Transient Solver and Mesh Settings** section.

3 In the f_{max} text field, type `N0*f0`.

ADD MATERIAL

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

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

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

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

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

MESH 1

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

2 In the **Settings** window for **Mesh**, locate the **Physics-Controlled Mesh** section.

3 In the table, clear the **Use** check box for **Electrical Circuit (cir)**.

4 Click **Build All**.

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

STUDY 1

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study 1** click **Step 1: Time Dependent**.

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

3 In the **Output times** text field, type `range(0,T0/30,10*T0)`.

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

RESULTS

Pressure On-Axis

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

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

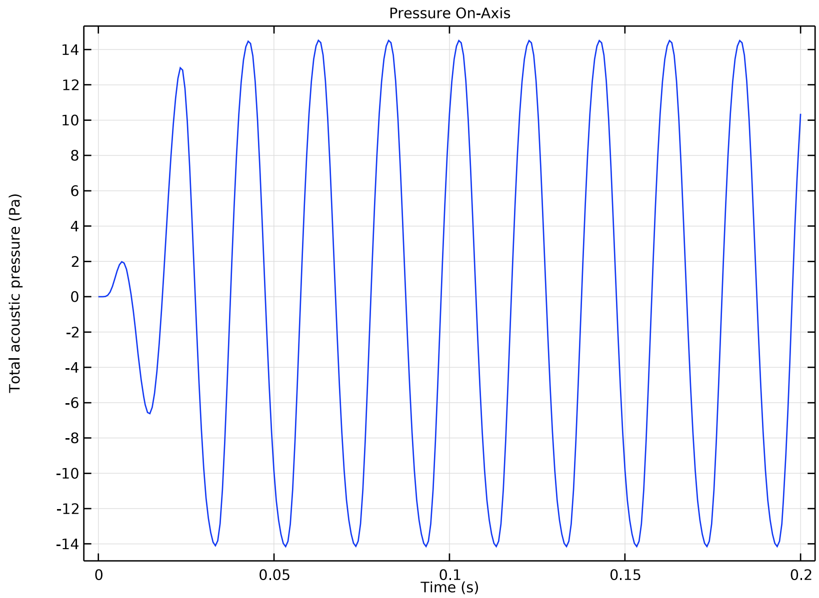
3 Click to expand the **Title** section. From the **Title type** list, choose **Label**.

Point Graph 1

1 Right-click **Pressure On-Axis** and choose **Point Graph**.

2 Select Point 6 only.

3 In the **Pressure On-Axis** toolbar, click **Plot**.



Pressure On-Axis FFT

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

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

3 Locate the **Data** section. From the **Time selection** list, choose **Interpolated**.

4 In the **Times (s)** text field, type `range(2*T0,T0/100,10*T0)`.

The interpolation option is used to only use the solution after the initial transient ramp behavior. The sampling is also increased to get a higher frequency resolution in the FFT.

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

6 Locate the **Plot Settings** section.

7 Select the **y-axis label** check box. In the associated text field, type `Fourier coefficient (dB SPL)`.

Point Graph 1

1 Right-click **Pressure On-Axis FFT** and choose **Point Graph**.

2 Select Point 6 only.

3 In the **Settings** window for **Point Graph**, locate the **x-Axis Data** section.

4 From the **Parameter** list, choose **Discrete Fourier transform**.

5 From the **Show** list, choose **Frequency spectrum**.

6 From the **Scale** list, choose **Multiply by sampling period**.

7 Select the **Frequency range** check box.

8 In the **Maximum** text field, type `(N0+1.5)*f0`.

9 Select the **In dB** check box.

10 From the **dB type** list, choose **20log**.

11 From the **dB reference** list, choose **Manual**.

12 In the **Reference value** text field, type `20e-6`.

13 In the **Pressure On-Axis FFT** toolbar, click **Plot**.

Graph Marker 1

1 In the **Model Builder** window, right-click **Point Graph 1** and choose **Graph Marker**.

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

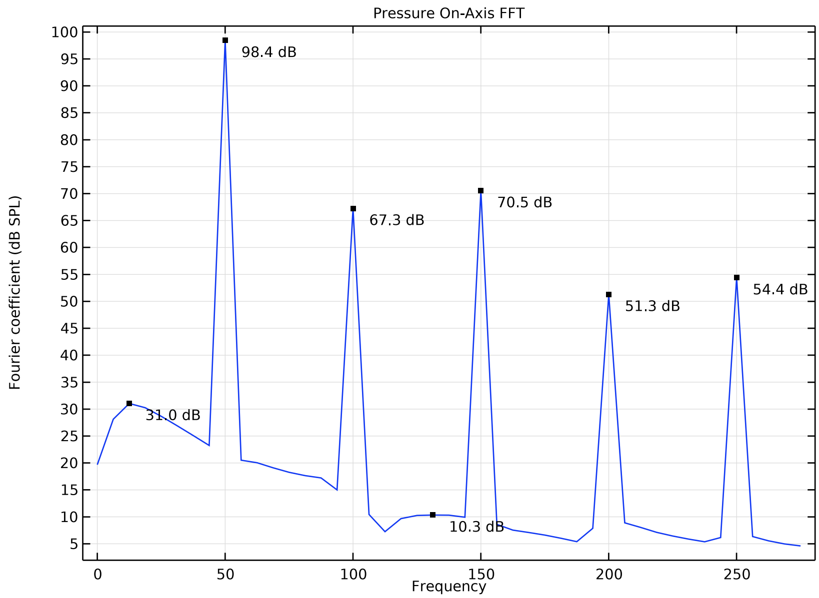
3 From the **Display** list, choose **Max**.

4 From the **Scope** list, choose **Local**.

5 Locate the **Text Format** section. In the **Display precision** text field, type `3`.

6 In the **Suffix** text field, type ` dB`.

7 In the **Pressure On-Axis FFT** toolbar, click **Plot**.



Speaker Position x(t)

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

2 In the **Settings** window for **1D Plot Group**, type `Speaker Position x(t)` in the **Label** text field.

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

Global 1

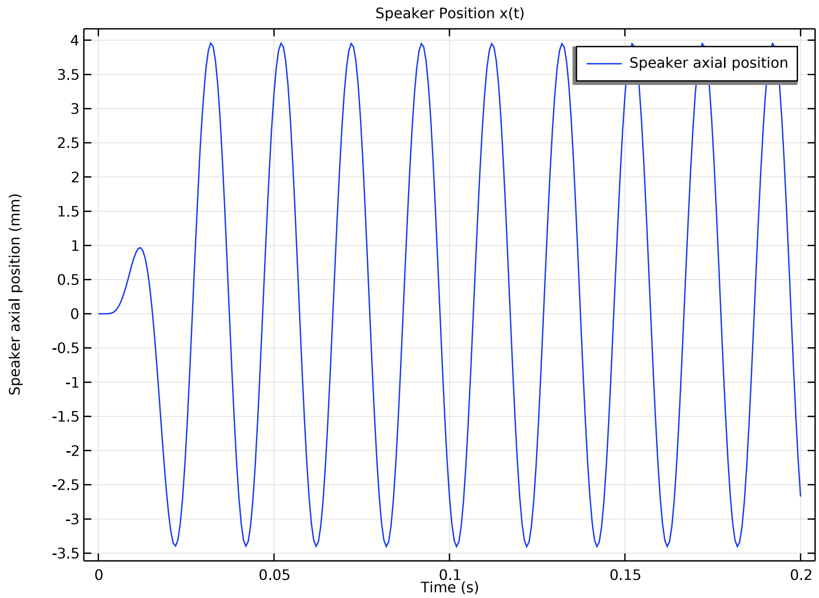
1 Right-click **Speaker Position x(t)** and choose **Global**.

2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)> Pressure Acoustics, Transient>Interior Lumped Speaker Boundary 1>actd.ilsb1.x_ax - Speaker axial position - m**.

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

Expression	Unit	Description
`actd.ilsb1.x_ax`	`mm`	`Speaker axial position`

4 In the **Speaker Position x(t)** toolbar, click **Plot**.



Speaker Velocity v(t)

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

2 In the **Settings** window for **1D Plot Group**, type `Speaker Velocity v(t)` in the **Label** text field.

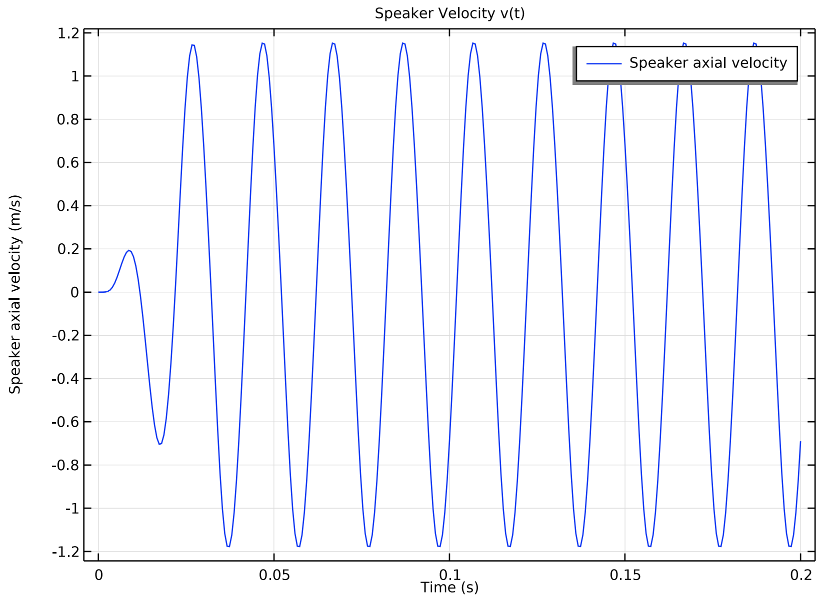
3 Locate the **Title** section. From the **Title type** list, choose **Label**.

Global 1

1 Right-click **Speaker Velocity v(t)** and choose **Global**.

2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Pressure Acoustics, Transient>Interior Lumped Speaker Boundary 1>actd.ilsb1.v_ax - Speaker axial velocity - m/s**.

3 In the **Speaker Velocity v(t)** toolbar, click **Plot**.



C_MS(x(t))

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

2 In the **Settings** window for **1D Plot Group**, type `C_MS(x(t))` in the **Label** text field.

3 Locate the **Data** section. From the **Time selection** list, choose **Interpolated**.

4 In the **Times (s)** text field, type `range(5*T0,T0/60,10*T0)`.

Global 1

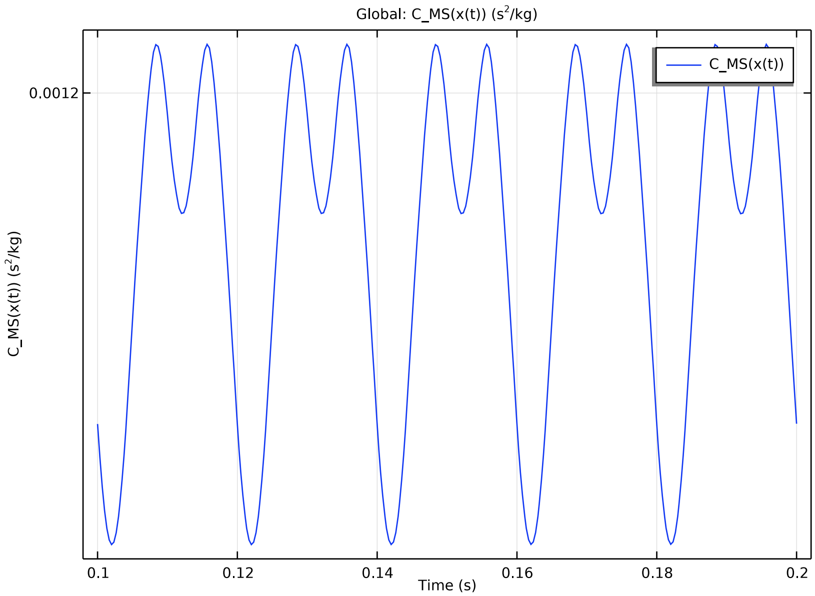
1 Right-click **C_MS(x(t))** and choose **Global**.

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

3 In the table, enter the following settings:

Expression	Unit	Description
`C_MS(actd.ilsb1.x_ax)`	`s^2/kg`	`C_MS(x(t))`

4 In the **C_MS(x(t))** toolbar, click **Plot**.



BL(x(t))

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

2 In the **Settings** window for **1D Plot Group**, type `BL(x(t))` in the **Label** text field.

3 Locate the **Data** section. From the **Time selection** list, choose **Interpolated**.

4 In the **Times (s)** text field, type `range(5*T0,T0/60,10*T0)`.

Global 1

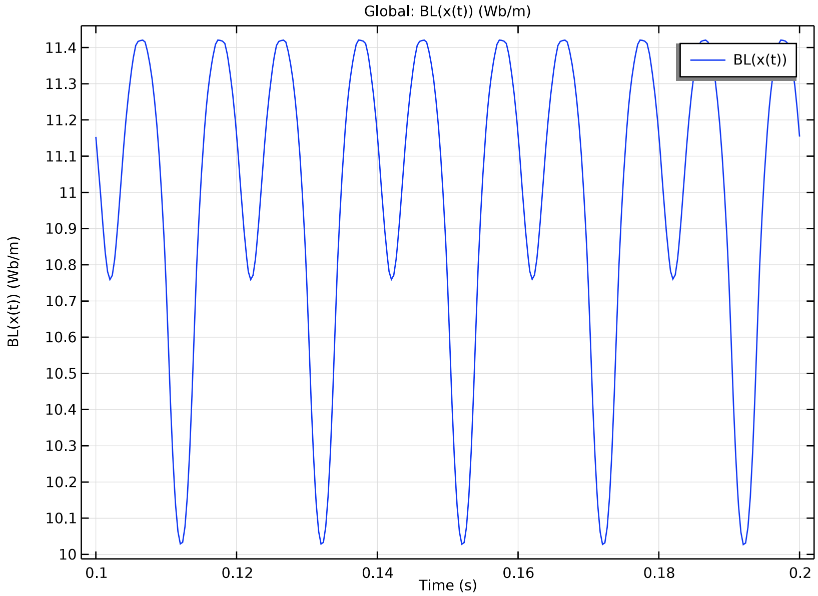
1 Right-click **BL(x(t))** and choose **Global**.

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

3 In the table, enter the following settings:

Expression	Unit	Description
`BL(actd.ilsb1.x_ax)`	`Wb/m`	`BL(x(t))`

4 In the **BL(x(t))** toolbar, click **Plot**.



R_MS(v(t))

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

2 In the **Settings** window for **1D Plot Group**, type `R_MS(v(t))` in the **Label** text field.

3 Locate the **Data** section. From the **Time selection** list, choose **Interpolated**.

4 In the **Times (s)** text field, type `range(5*T0,T0/60,10*T0)`.

Global 1

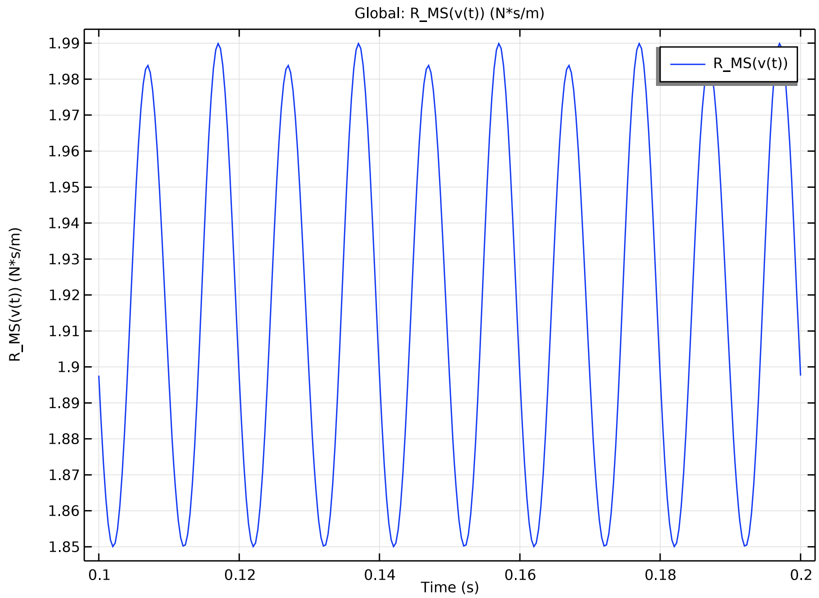
1 Right-click **R_MS(v(t))** and choose **Global**.

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

3 In the table, enter the following settings:

Expression	Unit	Description
`R_MS(actd.ilsb1.v_ax)`	`N*s/m`	`R_MS(v(t))`

4 In the **R_MS(v(t))** toolbar, click **Plot**.



GLOBAL DEFINITIONS

Interpolation 1 (BL)

1 In the **Model Builder** window, under **Global Definitions** click **Interpolation 1 (BL)**.

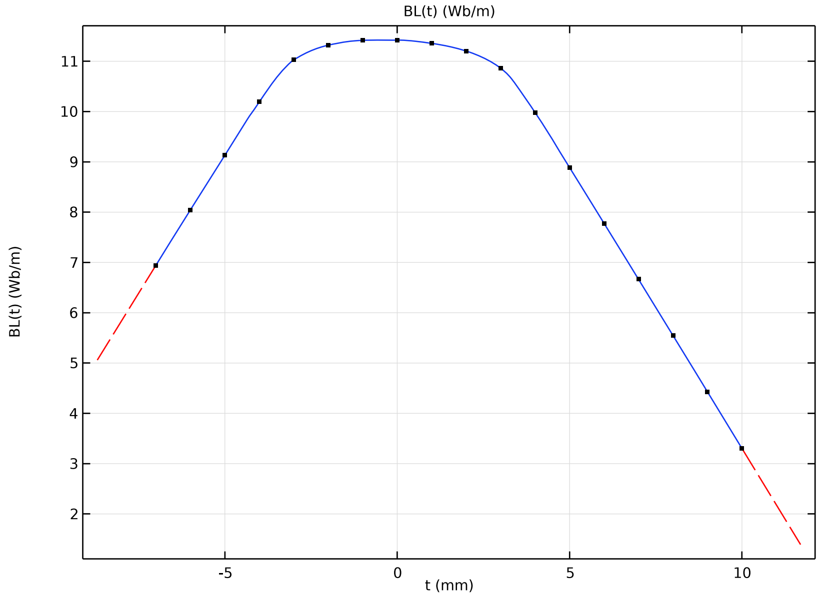
2 In the **Settings** window for **Interpolation**, click **Create Plot**.

RESULTS

Interpolation Data: BL(x)

1 In the **Settings** window for **1D Plot Group**, type `Interpolation Data: BL(x)` in the **Label** text field.

2 In the **Interpolation Data: BL(x)** toolbar, click **Plot**.



GLOBAL DEFINITIONS

Interpolation 2 (C_MS)

1 In the **Model Builder** window, under **Global Definitions** click **Interpolation 2 (C_MS)**.

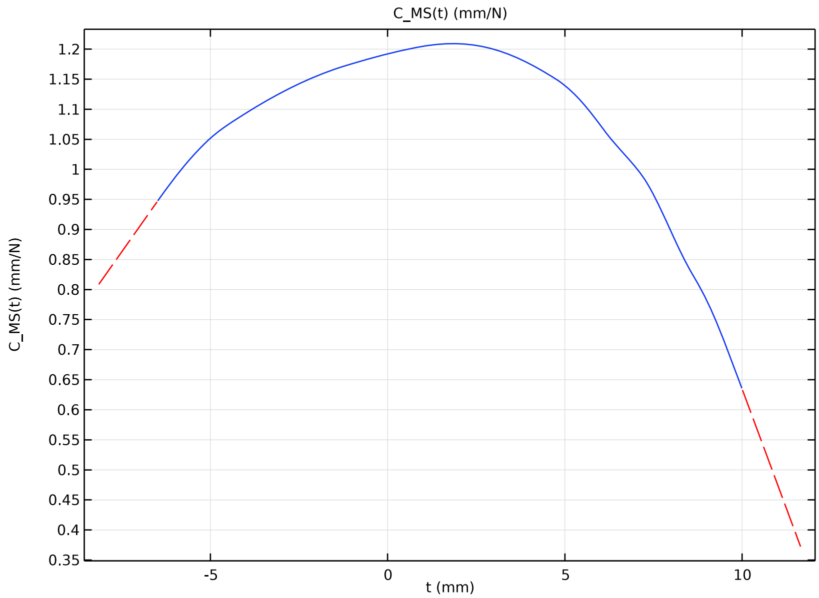
2 In the **Settings** window for **Interpolation**, click **Create Plot**.

RESULTS

Interpolation Data: C_MS(x)

1 In the **Settings** window for **1D Plot Group**, type `Interpolation Data: C_MS(x)` in the **Label** text field.

2 In the **Interpolation Data: C_MS(x)** toolbar, click **Plot**.



GLOBAL DEFINITIONS

Interpolation 3 (R_MS)

1 In the **Model Builder** window, under **Global Definitions** click **Interpolation 3 (R_MS)**.

2 In the **Settings** window for **Interpolation**, click **Create Plot**.

RESULTS

Interpolation Data: R_MS(v)

1 In the **Settings** window for **1D Plot Group**, type `Interpolation Data: R_MS(v)` in the **Label** text field.

2 In the **Interpolation Data: R_MS(v)** toolbar, click **Plot**.