Chapter 1

Introduction to Simulink

This chapter is an introduction to Simulink. This author feels that we can best introduce Simulink with a few examples. Tools for simulation and model–based designs will be presented in the subsequent chapters. Some familiarity with MATLAB is essential in understanding Simulink, and for this purpose, Appendix A is included as an introduction to MATLAB.

1.1 Simulink and its Relation to MATLAB

The MATLAB® and Simulink® environments are integrated into one entity, and thus we can analyze, simulate, and revise our models in either environment at any point. We invoke Simulink from within MATLAB. We begin with a few examples and we will discuss generalities in subsequent chapters. Throughout this text, a left justified horizontal bar will denote the beginning of an example, and a right justified horizontal bar will denote the end of the example. These bars will not be shown whenever an example begins at the top of a page or at the bottom of a page. Also, when one example follows immediately after a previous example, the right justified bar will be omitted.

Example 1.1

For the circuit of Figure 1.1, the initial conditions are \(i_L(0^-) = 0\), and \(v_c(0^-) = 0.5\) V. We will compute \(v_c(t)\).

\[
\begin{align*}
R &\quad L \\
1 \Omega &\quad 1/4 \text{H} \\
+ &\quad - \\
i(t) &\quad v_c(t) \\
4/3 \text{F} &\quad + \quad - \\
v_s(t) = u_0(t)
\end{align*}
\]

Figure 1.1. Circuit for Example 1.1

For this example,

\[
i = i_L = i_C = C \frac{dv_c}{dt}
\]  (1.1)

and by Kirchoff's voltage law (KVL),
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\[ R i_L + L \frac{di_L}{dt} + v_C = u_0(t) \]  \hspace{1cm} (1.2)

Substitution of (1.1) into (1.2) yields

\[ RC \frac{dv_C}{dt} + LC \frac{d^2v_C}{dt^2} + v_C = u_0(t) \]  \hspace{1cm} (1.3)

Substituting the values of the circuit constants and rearranging we get:

\[ \frac{1}{3} \frac{d^2v_C}{dt^2} + \frac{4}{3} \frac{dv_C}{dt} + v_C = u_0(t) \]  \hspace{1cm} (1.4)

\[ \frac{d^2v_C}{dt^2} + 4 \frac{dv_C}{dt} + 3v_C = 3u_0(t) \]  \hspace{1cm} \hspace{1cm} (1.5)

To appreciate Simulink’s capabilities, for comparison, three different methods of obtaining the solution are presented, and the solution using Simulink follows.

**First Method – Assumed Solution**

Equation (1.5) is a second-order, non-homogeneous differential equation with constant coefficients, and thus the complete solution will consist of the sum of the forced response and the natural response. It is obvious that the solution of this equation cannot be a constant since the derivatives of a constant are zero and thus the equation is not satisfied. Also, the solution cannot contain sinusoidal functions (sine and cosine) since the derivatives of these are also sinusoids. However, decaying exponentials of the form \( ke^{-at} \) where \( k \) and \( a \) are constants, are possible candidates since their derivatives have the same form but alternate in sign.

It can be shown* that if \( k_1 e^{-s_1t} \) and \( k_2 e^{-s_2t} \) where \( k_1 \) and \( k_2 \) are constants and \( s_1 \) and \( s_2 \) are the roots of the characteristic equation of the homogeneous part of the given differential equation, the natural response is the sum of the terms \( k_1 e^{-s_1t} \) and \( k_2 e^{-s_2t} \). Therefore, the total solution will be

\[ v_c(t) = \text{natural response + forced response} = v_{cn}(t) + v_{cf}(t) = k_1 e^{-s_1t} + k_2 e^{-s_2t} + v_{cf}(t) \]  \hspace{1cm} (1.6)

---

The values of \( s_1 \) and \( s_2 \) are the roots of the characteristic equation

\[
s^2 + 4s + 3 = 0
\]  
(1.7)

Solution of (1.7) yields \( s_1 = -1 \) and \( s_2 = -3 \) and with these values (1.6) is written as

\[
v_c(t) = k_1 e^{-t} + k_2 e^{-3t} + v_{cf}(t)
\]  
(1.8)

The forced component \( v_{cf}(t) \) is found from (1.5), i.e.,

\[
\frac{d^2 v_c}{dt^2} + 4 \frac{dv_c}{dt} + 3v_c = 3 \quad t > 0
\]  
(1.9)

Since the right side of (1.9) is a constant, the forced response will also be a constant and we denote it as \( v_{cf} = k_3 \). By substitution into (1.9) we get

\[
0 + 0 + 3k_3 = 3
\]

or

\[
v_{cf} = k_3 = 1
\]  
(1.10)

Substitution of this value into (1.8), yields the total solution as

\[
v_c(t) = v_{cn}(t) + v_{cf} = k_1 e^{-t} + k_2 e^{-3t} + 1
\]  
(1.11)

The constants \( k_1 \) and \( k_2 \) will be evaluated from the initial conditions. First, using \( v_c(0) = 0.5 \text{ V} \) and evaluating (1.11) at \( t = 0 \), we get

\[
v_c(0) = k_1 e^0 + k_2 e^0 + 1 = 0.5
\]

\[
k_1 + k_2 = -0.5
\]  
(1.12)

Also,

\[
i_L = i_c = C \frac{dv_c}{dt}, \quad \frac{dv_c}{dt} = \frac{i_L}{C}
\]

and

\[
\frac{dv_c}{dt} \bigg|_{t=0} = \frac{i_L(0)}{C} = \frac{0}{C} = 0
\]  
(1.13)

Next, we differentiate (1.11), we evaluate it at \( t = 0 \), and equate it with (1.13). Thus,

\[
\frac{dv_c}{dt} \bigg|_{t=0} = -k_1 - 3k_2
\]  
(1.14)
By equating the right sides of (1.13) and (1.14) we get

\[-k_1 - 3k_2 = 0 \quad (1.15)\]

Simultaneous solution of (1.12) and (1.15), gives \( k_1 = -0.75 \) and \( k_2 = 0.25 \). By substitution into (1.8), we obtain the total solution as

\[v_C(t) = (-0.75e^{-t} + 0.25e^{-3t} + 1)u_0(t) \quad (1.16)\]

Check with MATLAB:

```matlab
syms t % Define symbolic variable t
y0=-0.75*exp(-t)+0.25*exp(-3*t)+1; % The total solution y(t), for our example, vc(t)
y1=diff(y0) % The first derivative of y(t)
y1 = 3/4*exp(-t)-3/4*exp(-3*t)
y2=diff(y0,2) % The second derivative of y(t)
y2 = -3/4*exp(-t)+9/4*exp(-3*t)
y=y2+4*y1+3*y0 % Summation of y and its derivatives
y = 3
```

Thus, the solution has been verified by MATLAB. Using the expression for \( v_C(t) \) in (1.16), we find the expression for the current as

\[i = i_L = i_C = C \frac{dv_C}{dt} = \frac{4}{3} \left( \frac{3}{4} e^{-t} - \frac{3}{4} e^{-3t} \right) = e^{-t} - e^{-3t} \ A \quad (1.17)\]

**Second Method – Using the Laplace Transformation**

The transformed circuit is shown in Figure 1.2.

![Figure 1.2. Transformed Circuit for Example 1.1](image-url)
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By the voltage division expression,
\[
V_C(s) = \frac{3/4s}{(1 + 0.25s + 3/4s)} \left( \frac{1}{s} - \frac{0.5}{s} \right) + \frac{0.5}{s} = \frac{1.5}{s(s^2 + 4s + 3)} + \frac{0.5}{s} = \frac{0.5s^2 + 2s + 3}{s(s + 1)(s + 3)}
\]

Using partial fraction expansion,† we let
\[
\frac{0.5s^2 + 2s + 3}{s(s + 1)(s + 3)} = \frac{r_1}{s} + \frac{r_2}{s + 1} + \frac{r_3}{s + 3}
\]

\[
r_1 = \left. \frac{0.5s^2 + 2s + 3}{(s + 1)(s + 3)} \right|_{s = 0} = 1
\]

\[
r_2 = \left. \frac{0.5s^2 + 2s + 3}{s(s + 3)} \right|_{s = -1} = -0.75
\]

\[
r_3 = \left. \frac{0.5s^2 + 2s + 3}{s(s + 1)} \right|_{s = -3} = 0.25
\]

and by substitution into (1.18)
\[
V_C(s) = \frac{0.5s^2 + 2s + 3}{s(s + 1)(s + 3)} = \frac{1}{s} + \frac{-0.75}{s + 1} + \frac{0.25}{s + 3}
\]

Taking the Inverse Laplace transform‡ we find that
\[
v_C(t) = 1 - 0.75e^{-t} + 0.25e^{-3t}
\]

Third Method – Using State Variables
\[
Ri_L + L\frac{di_L}{dt} + v_c = u_0(t)
\]

* For derivation of the voltage division and current division expressions, please refer to Circuit Analysis I with MATLAB Applications, ISBN 0–9709511–2–4.


** Usually, in State–Space and State Variables Analysis, u(t) denotes any input. For distinction, we will denote the Unit Step Function as u_s(t). For a detailed discussion on State–Space and State Variables Analysis, please refer to Signals and Systems with MATLAB Applications, ISBN 0–9709511–6–7.
By substitution of given values and rearranging, we obtain

\[ \frac{1}{4} \frac{di_L}{dt} = (-1)i_L - v_C + 1 \]

or

\[ \frac{di_L}{dt} = -4i_L - 4v_C + 4 \] (1.19)

Next, we define the state variables \( x_1 = i_L \) and \( x_2 = v_C \). Then,

\[ \dot{x}_1 = \frac{di_L}{dt} \] (1.20)

and

\[ \dot{x}_2 = \frac{dv_C}{dt} \] (1.21)

Also,

\[ i_L = L \frac{dv_C}{dt} \]

and thus,

\[ x_1 = i_L = C \frac{dv_C}{dt} = Cx_2 = \frac{4}{3} x_2 \]

or

\[ \dot{x}_2 = \frac{3}{4} x_1 \] (1.22)

Therefore, from (1.19), (1.20), and (1.22), we get the state equations

\[ \dot{x}_1 = -4x_1 - 4x_2 + 4 \]

\[ \dot{x}_2 = \frac{3}{4} x_1 \]

and in matrix form,

\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2
\end{bmatrix} =
\begin{bmatrix}
-4 & -4 \\
3/4 & 0
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2
\end{bmatrix} +
\begin{bmatrix}
4 \\
0
\end{bmatrix} u_0(t) \] (1.23)

Solution† of (1.23) yields

* The notation \( \dot{x} \) (x dot) is often used to denote the first derivative of the function \( x \), that is, \( \dot{x} = dx/dt \).

† The detailed solution of (1.23) is given in Signals and Systems with MATLAB Applications, ISBN 0-9709511-6-7, Chapter 5.
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\[
\begin{bmatrix}
  x_1 \\
  x_2
\end{bmatrix} = \begin{bmatrix}
  e^{-t} - e^{-3t} \\
  1 - 0.75 e^{-t} + 0.25 e^{-3t}
\end{bmatrix}
\]

Then,

\[ x_1 = i_L = e^{-t} - e^{-3t} \]  (1.24)

and

\[ x_2 = v_C = 1 - 0.75 e^{-t} + 0.25 e^{-3t} \]  (1.25)

Modeling the Differential Equation of Example 1.1 with Simulink

To run Simulink, we must first invoke MATLAB. Make sure that Simulink is installed in your system. In the Command Window, we type:

\texttt{simulink}

Alternately, we can click on the Simulink icon shown in Figure 1.3. It appears on the top bar on MATLAB’s Command Window.

\begin{figure}[h]
  \centering
  \includegraphics[width=0.5\textwidth]{simulink_icon.png}
  \caption{The Simulink icon}
  \label{fig:simulink_icon}
\end{figure}

Upon execution of the Simulink command, the \textbf{Commonly Used Blocks} are shown in Figure 1.4.

In Figure 1.4, the left side is referred to as the \textbf{Tree Pane} and displays all Simulink libraries installed. The right side is referred to as the \textbf{Contents Pane} and displays the blocks that reside in the library currently selected in the Tree Pane.

Let us express the differential equation of Example 1.1 as

\[
\frac{d^2 v_C}{dt^2} = -4 \frac{dv_C}{dt} - 3 v_C + 3 u_0(t) \]  (1.26)

A block diagram representing (1.26) is shown in Figure 1.5. Now, we will use Simulink to draw a similar block diagram.
To model the differential equation (1.26) using Simulink, we perform the following steps:

1. On the Simulink Library Browser, we click on the leftmost icon shown as a blank page on the top title bar. A new model window named untitled will appear as shown in Figure 1.6.
Figure 1.6. The Untitled model window in Simulink.

The window of Figure 1.6 is the model window where we enter our blocks to form a block diagram. We save this as model file name Equation_1_26. This is done from the File drop menu of Figure 1.6 where we choose Save as and name the file as Equation_1_26. Simulink will add the extension .mdl. The new model window will now be shown as Equation_1_26, and all saved files will have this appearance. See Figure 1.7.

Figure 1.7. Model window for Equation_1_26.mdl file

2. With the Equation_1_26 model window and the Simulink Library Browser both visible, we click on the Sources appearing on the left side list, and on the right side we scroll down until we see the unit step function. See Figure 1.8. We select it, and we drag it into the Equation_1_26 model window which now appears as shown in Figure 1.8. We save file Equation_1_26 using the File drop menu on the Equation_1_26 model window (right side of Figure 1.8).

3. With reference to block diagram of Figure 1.5, we observe that we need to connect an amplifier with Gain 3 to the unit step function block. The gain block in Simulink is under Commonly Used Blocks (first item under Simulink on the Simulink Library Browser). See Figure 1.8. If the Equation_1_26 model window is no longer visible, it can be recalled by clicking on the white page icon on the top bar of the Simulink Library Browser.

4. We choose the gain block and we drag it to the right of the unit step function. The triangle on the right side of the unit step function block and the > symbols on the left and right sides of the gain block are connection points. We point the mouse close to the connection point of the unit step function until is shows as a cross hair, and draw a straight line to connect the two
blocks. We double-click on the gain block and on the **Function Block Parameters**, we change the gain from 1 to 3. See Figure 1.9.

5. Next, we need to add a three-input adder. The adder block appears on the right side of the **Simulink Library Browser** under **Math Operations**. We select it, and we drag it into the **Equation_1_26** model window. We double click it, and on the **Function Block Parameters**
window which appears, we specify 3 inputs. We then connect the output of the of the gain block to the first input of the adder block as shown in Figure 1.10.

Figure 1.10. File Equation_1_26 with added gain block

6. From the Commonly Used Blocks of the Simulink Library Browser, we choose the Integrator block, we drag it into the Equation_1_26 model window, and we connect it to the output of the Add block. We repeat this step and to add a second Integrator block. We click on the text “Integrator” under the first integrator block, and we change it to Integrator 1. Then, we change the text “Integrator 1” under the second Integrator to “Integrator 2” as shown in Figure 1.11.

Figure 1.11. File Equation_1_26 with the addition of two integrators

7. To complete the block diagram, we add the Scope block which is found in the Commonly Used Blocks on the Simulink Library Browser, we click on the Gain block, and we copy and paste it twice. We flip the pasted Gain blocks by using the Flip Block command from the Format drop menu, and we label these as Gain 2 and Gain 3. Finally, we double-click on these gain blocks and on the Function Block Parameters window, we change the gains from to $g_16$ and $g_16$ as shown in Figure 1.12.

Figure 1.12. File Equation_1_26 complete block diagram

8. The initial conditions $i_t(0^-) = C \frac{dv_c}{dt} \bigg|_{t=0} = 0$, and $v_c(0^-) = 0.5$ V are entered by double clicking the Integrator blocks and entering the values 0 for the first integrator, and 0.5 for the
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second integrator. We also need to specify the simulation time. This is done by specifying the simulation time to be 10 seconds on the Configuration Parameters from the Simulation drop menu. We can start the simulation on Start from the Simulation drop menu or by clicking on the icon.

9. To see the output waveform, we double click on the Scope block, and then clicking on the Autoscale icon, we obtain the waveform shown in Figure 1.13.

![Scope waveform](image)

Figure 1.13. The waveform for the function $v_C(t)$ for Example 1.1

Another easier method to obtain and display the output $v_C(t)$ for Example 1.1, is to use State-Space block from Continuous in the Simulink Library Browser, as shown in Figure 1.14.

![Schematic](image)

Figure 1.14. Obtaining the function $v_C(t)$ for Example 1.1 with the State–Space block.

The simout To Workspace block shown in Figure 1.14 writes its input to the workspace. As we know from our MATLAB studies, the data and variables created in the MATLAB Command window, reside in the MATLAB Workspace. This block writes its output to an array or structure.
that has the name specified by the block's Variable name parameter. It is highly recommended that this block is included in the saved model. This gives us the ability to delete or modify selected variables. To see what variables reside in the MATLAB Workspace, we issue the command `who`.

From Equation 1.23,

\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2
\end{bmatrix} = \begin{bmatrix}
-4 & -4 \\
3/4 & 0
\end{bmatrix} \begin{bmatrix}
x_1 \\
x_2
\end{bmatrix} + \begin{bmatrix}
4 \\
0
\end{bmatrix} u_0(t)
\]

The output equation is

\[ y = Cx + du \]

or

\[ y = \begin{bmatrix}
0 & 1
\end{bmatrix} \begin{bmatrix}
x_1 \\
x_2
\end{bmatrix} + [0]u \]

We double-click on the State–Space block, and in the Functions Block Parameters window we enter the constants shown in Figure 1.15.

![Function Block Parameters: State-Space](image)

Figure 1.15. The Function block parameters for the State–Space block.
The initial conditions \([x_1 \ x_2]\) are specified in MATLAB's Command Window as
\[x_1=0; \ x_2=0.5;\]

As before, to start the simulation we click clicking on the \(\text{\(\rightarrow\)}\) icon, and to see the output waveform, we double click on the **Scope** block, and then clicking on the Autoscale \(\text{\(\text{\(\square\)}\)}\) icon, we obtain the waveform shown in Figure 1.16.

![Scope](image)

Figure 1.16. The waveform for the function \(v_c(t)\) for Example 1.1 with the State-Space block.

The state-space block is the best choice when we need to display the output waveform of three or more variables as illustrated by the following example.

**Example 1.2**

A fourth–order network is described by the differential equation

\[
\frac{d^4 y}{dt^4} + a_3 \frac{d^3 y}{dt^3} + a_2 \frac{d^2 y}{dt^2} + a_1 \frac{dy}{dt} + a_0 y(t) = u(t)
\]

(1.27)

where \(y(t)\) is the output representing the voltage or current of the network, and \(u(t)\) is any input, and the initial conditions are \(y(0) = y'(0) = y''(0) = y'''(0) = 0\).

a. We will express (1.27) as a set of state equations
b. It is known that the solution of the differential equation

\[ \frac{d^4y}{dt^4} + 2 \frac{d^2y}{dt^2} + y(t) = \text{sint} \]  

(1.28)

subject to the initial conditions \( y(0) = y'(0) = y''(0) = y'''(0) = 0 \), has the solution

\[ y(t) = 0.125[(3 - t^2) - 3\cos t] \]  

(1.29)

In our set of state equations, we will select appropriate values for the coefficients \( a_3, a_2, a_1, \) and \( a_0 \) so that the new set of the state equations will represent the differential equation of (1.28) and using Simulink, we will display the waveform of the output \( y(t) \).

1. The differential equation of (1.28) is of fourth-order; therefore, we must define four state variables that will be used with the four first-order state equations.

We denote the state variables as \( x_1, x_2, x_3, \) and \( x_4 \), and we relate them to the terms of the given differential equation as

\[ x_1 = y(t) \quad x_2 = \frac{dy}{dt} \quad x_3 = \frac{d^2y}{dt^2} \quad x_4 = \frac{d^3y}{dt^3} \]  

(1.30)

We observe that

\[ \dot{x}_1 = x_2 \]
\[ \dot{x}_2 = x_3 \]
\[ \dot{x}_3 = x_4 \]
\[ \frac{d^4y}{dt^4} = \dot{x}_4 = -a_0x_1-a_1x_2-a_2x_3-a_3x_4 + u(t) \]  

(1.31)

and in matrix form

\[ \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -a_0 & -a_1 & -a_2 & -a_3 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} u(t) \]  

(1.32)

In compact form, (1.32) is written as

\[ \dot{x} = Ax + bu \]  

(1.33)

Also, the output is

\[ y = Cx + du \]  

(1.34)

where
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\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\dot{x}_3 \\
\dot{x}_4
\end{bmatrix}
= \begin{bmatrix}
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
-a_0 & -a_1 & -a_2 & -a_3
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
x_3 \\
x_4
\end{bmatrix}
+ \begin{bmatrix}
0 \\
0 \\
0 \\
1
\end{bmatrix}, \quad \text{and } u = u(t) \quad (1.35)
\]

and since the output is defined as
\[y(t) = x_1\]

relation (1.34) is expressed as
\[
y = \begin{bmatrix}
1 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
x_3 \\
x_4
\end{bmatrix}
+ [0]u(t) \quad (1.36)
\]

2. By inspection the differential equation of (1.27) will be reduced to the differential equation of (1.28) if we let
\[a_3 = 0 \quad a_2 = 2 \quad a_1 = 0 \quad a_0 = 1\]

and thus the differential equation of (1.28) can be expressed in state–space form as
\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\dot{x}_3 \\
\dot{x}_4
\end{bmatrix}
= \begin{bmatrix}
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
-a_0 & -2 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
x_3 \\
x_4
\end{bmatrix}
+ \begin{bmatrix}
0 \\
0 \\
0 \\
1
\end{bmatrix}
sint \quad (1.37)
\]

where
\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\dot{x}_3 \\
\dot{x}_4
\end{bmatrix}
= \begin{bmatrix}
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
-a_0 & -2 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
x_3 \\
x_4
\end{bmatrix}
+ \begin{bmatrix}
0 \\
0 \\
0 \\
1
\end{bmatrix}, \quad \text{and } u = \text{sint} \quad (1.38)
\]

Since the output is defined as
\[y(t) = x_1\]

in matrix form it is expressed as
We invoke MATLAB, we start Simulink by clicking on the Simulink icon, on the Simulink Library Browser, we click on the Create a new model (blank page icon on the left of the top bar), and we save this model as Example_1_2. On the Simulink Library Browser we select Sources, we drag the Signal Generator block on the Example_1_2 model window, we click and drag the State–Space block from the Continuous on Simulink Library Browser, and we click and drag the Scope block from the Commonly Used Blocks on the Simulink Library Browser. We also add the Display block found under Sinks on the Simulink Library Browser. We connect these four blocks and the complete block diagram is as shown in Figure 1.17.

We now double-click on the Signal Generator block and we enter the following in the Function Block Parameters:

Wave form: sine
Time (t): Use simulation time
Amplitude: 1
Frequency: 2
Units: Hertz

Next, we double-click on the state–space block and we enter the following parameter values in the Function Block Parameters:

A: [0 1 0 0; 0 0 1 0; 0 0 0 1; -a0 -a1 -a2 -a3]
B: [0 0 0 1]'
C: [1 0 0 0]
D: [0]
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Initial conditions: x0
Absolute tolerance: auto

Now, we switch to the MATLAB Command Window and we type the following:

```
>> a0=1; a1=0; a2=2; a3=0; x0=[0 0 0 0]';
```

We change the Simulation Stop time to 25, and we start the simulation by clicking on the icon. To see the output waveform, we double click on the Scope block, then clicking on the Autoscale icon, we obtain the waveform shown in Figure 1.18.

![Waveform for Example 1.2](image)

Figure 1.18. Waveform for Example 1.2

The Display block in Figure 1.17 shows the value at the end of the simulation stop time.

Examples 1.1 and 1.2 have clearly illustrated that the State–Space is indeed a powerful block. We could have obtained the solution of Example 1.2 using four Integrator blocks by this approach would have been more time consuming.

Example 1.3

Using Algebraic Constraint blocks found in the Math Operations library, Display blocks found in the Sinks library, and Gain blocks found in the Commonly Used Blocks library, we will create a model that will produce the simultaneous solution of three equations with three unknowns.

The model will display the values for the unknowns $z_1$, $z_2$, and $z_3$ in the system of the equations
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\begin{align*}
    a_1z_1 + a_2z_2 + a_3z_3 + k_1 &= 0 \\
    a_4z_1 + a_5z_2 + a_6z_3 + k_2 &= 0 \\
    a_7z_1 + a_8z_2 + a_9z_3 + k_3 &= 0
\end{align*} \quad (1.40)

The model is shown in Figure 1.19.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1_19.png}
\caption{Model for Example 1.3}
\end{figure}

Next, we go to MATLAB’s Command Window and we enter the following values:

\begin{align*}
    a_1 &= 2; \\
    a_2 &= -3; \\
    a_3 &= -1; \\
    a_4 &= 1; \\
    a_5 &= 5; \\
    a_6 &= 4; \\
    a_7 &= -6; \\
    a_8 &= 1; \\
    a_9 &= 2; \\
    k_1 &= -8; \\
    k_2 &= -7; \\
    k_3 &= 5;
\end{align*}

After clicking on the simulation icon, we observe the values of the unknowns as \( z_1 = 2 \), \( z_2 = -3 \), and \( z_3 = 5 \). These values are shown in the Display blocks of Figure 1.19.

The **Algebraic Constraint** block constrains the input signal \( f(z) \) to zero and outputs an algebraic state \( z \). The block outputs the value necessary to produce a zero at the input. The output must affect the input through some feedback path. This enables us to specify algebraic equations for index 1 differential/algebraic systems (DAEs). By default, the Initial guess parameter is zero. We
can improve the efficiency of the algebraic loop solver by providing an Initial guess for the algebraic state $z$ that is close to the solution value.

An outstanding feature in Simulink is the representation of a large model consisting of many blocks and lines, to be shown as a single Subsystem block. For instance, we can group all blocks and lines in the model of Figure 1.19 except the display blocks, we choose Create Subsystem from the Edit menu, and this model will be shown as in Figure 1.20* where in MATLAB's Command Window we have entered:

$a1=5; a2=-1; a3=4; a4=11; a5=6; a6=-8; a7=4; a8=15; a9=15; a10=-6; a11=9;$

$\begin{align*}
    k1 &= 14; \\
    k2 &= 6; \\
    k3 &= 9;
\end{align*}$

The Display blocks in Figure 1.20 show the values of $z_1$, $z_2$, and $z_3$ for the values specified in MATLAB's Command Window.

The Subsystem block is described in detail in Chapter 2, Section 2.1, Page 2–2.

### 1.2 Simulink Demos

At this time, the reader with no prior knowledge of Simulink, should be ready to learn Simulink's additional capabilities. We will explore other features in the subsequent chapters. However, it is highly recommended that the reader becomes familiar with the block libraries found in the Simulink Library Browser. Then, the reader can follow the steps delineated in The MathWorks Simulink User's Manual to run the Demo Models beginning with the thermo model. This model can be started by typing `thermo` in the MATLAB Command Window.

In the subsequent chapters, we will study each of the blocks under each of libraries in the Tree Pane. They are listed in Table 1.1 below in alphabetical order, library, chapter, section/subsection, and page number in which they are described.

---

* The contents of the Subsystem block are not lost. We can double-click on the Subsystem block to see its contents. The Subsystem block replaces the inputs and outputs of the model with Inport and Outport blocks. These blocks are described in Section 2.1, Chapter 2, Page 2-2.
### TABLE 1.1 Simulink blocks

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1.3 Summary

- MATLAB and Simulink are integrated and thus we can analyze, simulate, and revise our models in either environment at any point. We invoke Simulink from within MATLAB.

- When Simulink is invoked, the Simulink Library Browser appears. The left side is referred to as the Tree Pane and displays all libraries installed. The right side is referred to as the Contents Pane and displays the blocks that reside in the library currently selected in the Tree Pane.

- We open a new model window by clicking on the blank page icon that appears on the leftmost position of the top title bar. On the Simulink Library Browser, we highlight the desired library in the Tree Pane, and on the Contents Pane we click and drag the desired block into the new model. Once saved, the model window assumes the name of the file saved. Simulink adds the extension .mdl.

- The > and < symbols on the left and right sides of a block are connection points.

- We can change the parameters of any block by double-clicking it, and making changes in the Function Block Parameters window.

- We can specify the simulation time on the Configuration Parameters from the Simulation drop menu. We can start the simulation on Start from the Simulation drop menu or by clicking on the icon. To see the output waveform, we double click on the Scope block, and then clicking on the Autoscale icon.

- It is highly recommended that the simout To Workspace block be added to the model so all data and variables are saved in the MATLAB workspace. This gives us the ability to delete or modify selected variables. To see what variables reside in the MATLAB Workspace, we issue the command who.

- The state-space block is the best choice when we need to display the output waveform of three or more variables.

- We can use Algebraic Constrain blocks found in the Math Operations library, Display blocks found in the Sinks library, and Gain blocks found in the Commonly Used Blocks library, to draw a model that will produce the simultaneous solution of two or more equations with two or more unknowns.

- The Algebraic Constraint block constrains the input signal f(z) to zero and outputs an algebraic state z. The block outputs the value necessary to produce a zero at the input. The output must affect the input through some feedback path. This enables us to specify algebraic equations for index 1 differential/algebraic systems (DAEs). By default, the Initial guess parameter is zero. We can improve the efficiency of the algebraic loop solver by providing an Initial guess for the algebraic state z that is close to the solution value.
1.4 Exercises

1. Use Simulink with the Step function block, the Continuous–Time Transfer Fcn block, and the Scope block shown, to simulate and display the output waveform $v_C$ of the RLC circuit shown below where $u_0(t)$ is the unit step function, and the initial conditions are $i_L(0) = 0$, and $v_C(0)$.

2. Repeat Exercise 1 using integrator blocks in lieu of the transfer function block.

3. Repeat Exercise 1 using the State Space block in lieu of the transfer function block.

4. Using the State–Space block, model the differential equation shown below.

\[
\frac{d^2 v_C}{dt^2} + \frac{dv_C}{dt} + v_C = 2 \sin(t + 30^\circ) - 5 \cos(t + 60^\circ)
\]

subject to the initial conditions $v_C(0^-) = 0$, and $v'_C(0^-) = 0.5 \text{ V}$
1.5 Solutions to End-of-Chapter Exercises

Dear Reader:

The remaining pages on this chapter contain solutions to all end–of–chapter exercises.

You must, for your benefit, make an honest effort to solve these exercises without first looking at the solutions that follow. It is recommended that first you go through and solve those you feel that you know. For your solutions that you are uncertain, look over your procedures for inconsistencies and computational errors, review the chapter, and try again. Refer to the solutions as a last resort and rework those problems at a later date.

You should follow this practice with all end–of–chapter exercises in this book.
1. The \( s \)-domain equivalent circuit is shown below.

\[
\begin{align*}
\frac{1}{s} & \quad V_{IN}(s) \\
Ls & \quad 1/sC \\
V_C(s) = V_{OUT}(s)
\end{align*}
\]

and by substitution of the given circuit constants,

\[
\begin{align*}
\frac{1}{s} & \quad V_{IN}(s) \\
s & \quad 1/s \\
V_C(s) = V_{OUT}(s)
\end{align*}
\]

By the voltage division expression,

\[
V_{OUT}(s) = \frac{(s \cdot 1/s)/(s + 1/s)}{(s \cdot 1/s)/(s + 1/s) + 1} \cdot V_{IN}(s) = \frac{s}{s^2 + s + 1} \cdot V_{IN}(s)
\]

from which

\[
\text{Transfer function } = G(s) = \frac{V_{OUT}(s)}{V_{IN}(s)} = \frac{s}{s^2 + s + 1}
\]

We invoke Simulink from the MATLAB environment, we open a new file by clicking on the blank page icon at the upper left on the task bar, we name this file Exercise_1_1, and from the Sources, Continuous, and Commonly Used Blocks in the Simulink Library Browser, we select and interconnect the desired blocks as shown below.

As we know, the unit step function is undefined at \( t = 0 \). Therefore, we double click on the Step block, and in the Source Block Parameters window we enter the values shown in the window below.
Next, we double click on the **Transfer Fcn** block and on the and in the **Source Block Parameters** window we enter the values shown in the window below.

On the Exercise_1_1 window, we click on the **Start Simulation** icon, and by double-clicking on the **Scope** block, we obtain the Scope window shown below.
It would be interesting to compare the above waveform with that obtained with MATLAB using the `plot` command. We want the output of the given circuit which we have defined as $v_{\text{out}}(t) = v_c(t)$. The input is the unit step function whose Laplace transform is $1/s$. Thus, in the complex frequency domain,

$$V_{\text{OUT}}(s) = G(s) \cdot V_{\text{IN}}(s) = \frac{s}{s^2 + s + 1} \cdot \frac{1}{s} = \frac{1}{s^2 + s + 1}$$

We obtain the Inverse Laplace transform of $1/(s^2 + s + 1)$ with the following MATLAB script:

```matlab
syms s
fd=ilaplace(1/(s^2+s+1))
fd = 2/3*3^(1/2)*(1/2)*exp(-1/2*t)*sin(1/2*3^(1/2)*t)
t=0:0.01:15;
td=2./3.*3.^(1./2).*exp(-1./2.*t).*sin(1./2.*3.^(1./2).*t);
plot(t,td); grid
```

The plot shown below is identical to that shown above which was obtained with Simulink.
By Kirchoff’s Current Law (KCL),

\[ i_L + i_C = i_R \]

\[ \frac{1}{L} \int_0^t v_L \, dt + C \frac{dv_C}{dt} = \frac{1 - v_C}{R} \]

By substitution of the circuit constants, observing that \( v_L = v_C \), and differentiating the above integro-differential equation, we get

\[ \frac{d^2 v_C}{dt^2} + \frac{dv_C}{dt} + v_C = 0 \]

Invoking MATLAB, starting Simulink, and following the procedures of the examples and Exercise 1, we create the new model Exercise_1_2, shown below.
Next, we double-click on Integrator 1 and in the Function Block Parameters window we set the initial value to 0. We repeat this step for Integrator 2 and we also set the initial value to 0. We start the simulation, and double-clicking on the Scope we obtain the graph shown below.

The plot above looks like the curve of a quadratic function. This is reasonable since the first integration of the unit step function yields a ramp function, and the second integration yields a quadratic function.
We assign state variables $x_1$ and $x_2$ as shown below where $x_1 = i_L$ and $x_2 = v_C$.

![Block Diagram]

Then,

$$\dot{x}_1 = x_2$$
$$\frac{x_2 - u_0 t}{1} + x_1 + \dot{x}_2 = 0$$
$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = -x_1 - x_2 + u_0 t$$

$$\dot{x} = Ax + Bu \rightarrow \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -1 & -1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u_0 t$$

$$y = Cx + Du \rightarrow \begin{bmatrix} y \end{bmatrix} = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \end{bmatrix} u_0 t$$

and the initial conditions are

$$x_0 = \begin{bmatrix} x_{10} \\ x_{20} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

We form the block diagram below and we name it Exercise_1_3.

We double-click on the State-Space block and we enter the following parameters:

$A=\begin{bmatrix} 0 & 1 \\ -1 & -1 \end{bmatrix}$

$B=\begin{bmatrix} 0 \\ 1 \end{bmatrix}'$

$C=\begin{bmatrix} 0 \\ 1 \end{bmatrix}'$

$D=\begin{bmatrix} 0 \end{bmatrix}$

Initial conditions: $x_0$

The initial conditions are entered in MATLAB’s Command Window as follows:

$x0=[0 0]';$
To avoid the unit step function discontinuity at \( t = 0 \), we double-click the Step block, and in the Source Block Parameters window, we change the Initial value from 0 to 1.

The Display block shows the output value at the end of the simulation time, in this case 15. We click on the Simulation start icon, we double-click on the Scope block, and the output waveform is as shown below. We observe that the waveform is the same as in Exercises 1 and 2.

4.

\[
\frac{d^2 v_C}{dt^2} + \frac{dv_C}{dt} + v_C = 2 \sin(t + 30^\circ) - 5 \cos(t + 60^\circ)
\]

subject to the initial conditions \( v_C(0^-) = 0 \), and \( v'_C(0^-) = 0.5 \text{ V} \)
We let $x_1 = v_C$ and $x_2 = \frac{dv_C}{dt}$. Then, $\dot{x}_1 = \frac{dv_C}{dt} = x_2$, and $\dot{x}_2 = \frac{d^2v_C}{dt^2}$. Expressing the given equation as

$$\frac{d^2v_C}{dt^2} = -\frac{dv_C}{dt} - v_C + 2\sin(t + 30^\circ) - 5\cos(t + 60^\circ) = -x_2 - x_1 + 2\sin(t + 30^\circ) - 5\cos(t + 60^\circ)$$

we obtain the state-space equations

$$\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= -x_2 - x_1 + 2\sin(t + 30^\circ) - 5\cos(t + 60^\circ)
\end{align*}$$

In matrix form,

$$\dot{x} = Ax + Bu \Rightarrow \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -1 & -1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} (2\sin(t + 30^\circ) - 5\cos(t + 60^\circ))$$

$$y = Cx + Du \Rightarrow \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} (2\sin(t + 30^\circ) - 5\cos(t + 60^\circ))$$

subject to the initial conditions

$$x_0 = \begin{bmatrix} x_{10} \\ x_{20} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Our simulation model is as shown below.

1. We double-click on the Sine Wave 1 block and in the Source Block Parameters, we make the following entries:
Sine type: Time based
Time (t): Use simulation time
Amplitude: 2
Bias: 0
Frequency: 2
Phase: \( \pi/6 \)
and we click on OK

2. We double-click on the Sine Wave 2 block and in the Source Block Parameters, we make the following entries:
Sine type: Time based
Time (t): Use simulation time
Amplitude: -5
Bias: 0
Frequency: 2
Phase: \( 5\pi/6 \)
and we click on OK

3. We double-click on the Signal Generator block and in the Source Block Parameters, we make the following entries:
Waveform: Sine
Time (t): Use external signal
Amplitude: 1
Frequency: 2
and we click on OK

4. We double-click on the State-Space block and in the Source Block Parameters, we make the following entries:
\[ A = \begin{bmatrix} 0 & 1 \\ -1 & -1 \end{bmatrix}, \quad B = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad C = \begin{bmatrix} 0 & 1 \end{bmatrix}, \quad D = [0], \quad \text{Initial conditions } [x_{10} \ x_{20}] \]
and we click on OK

5. On MATLAB’s Command Window we enter the initial conditions as
\[ x_{10}=0; \ x_{20}=0; \]
6. We click on the Start Simulation icon, and double-clicking on the scope we see the waveform below after clicking on the Autoscale icon.