

The Impulse Response and Convolution (Part 2)

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Digital Technium 123

Office Hours: 12:00-13:00 Mondays

You can view the notes for this presentation in [HTML](#) and [PDF](#).

The source code of this presentation is available in Markdown format from GitHub: [convolution.md](#).

The GitHub repository [EG-247 Resources](#) also contains the source code for all the Matlab/Simulink examples and the Laboratory Exercises.

Scope and Background Reading

This session continues our introduction to time convolution.

As we shall see, in the determination of a system's response to a signal input, time convolution involves integration by parts and is a tricky operation. But time convolution becomes *multiplication* in the Laplace Transform domain, and is much easier to apply.

The material in this presentation and notes is based on Chapter 6 of [Steven T. Karris, Signals and Systems: with Matlab Computation and Simulink Modelling, 5th Edition](#). and builds on the time response of a state-space model that was developed in the [previous session](#).

Agenda

The material to be presented will need two sessions.

Last Session

- The Impulse Response of a System in Time Domain
- Even and Odd Functions of Time

This Session

- Time Convolution
- Graphical Evaluation of the Convolution Integral
- System Response by Convolution
- System Response by Laplace

Time Convolution

Time Convolution

Consider a system whose input is the Dirac delta ($\delta(t)$), and its output is the impulse response $h(t)$. We can represent the inpt-output relationship as a block diagram

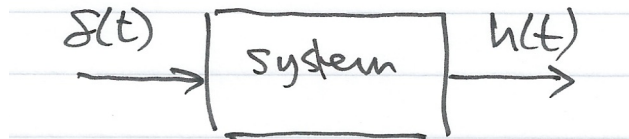


Figure 1: Impulse response

In general

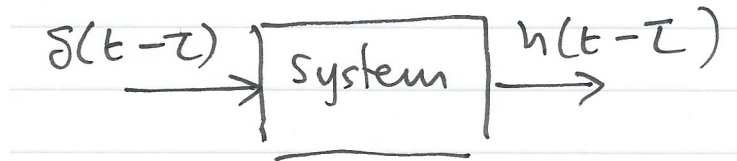


Figure 2: General impulse response

Add an arbitrary input

Let $u(t)$ be any input whose value at $t = \tau$ is $u(\tau)$, Then because of the sampling property of the delta function

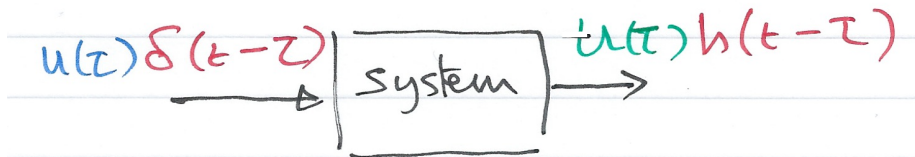


Figure 3: Response to an arbitrary input (1)

(output is $u(\tau)h(t - \tau)$)

Integrate both sides

Integrating both sides over all values of τ ($-\infty < \tau < \infty$) and making use of the fact that the delta function is even, i.e.

$$\delta(t - \tau) = \delta(\tau - t)$$

We have:

Since $\delta(t - \tau) = \delta(\tau - t)$ because $\delta(t)$ is even.

Figure 4: Response to an arbitrary input (2)

Use the sifting property of delta

The second integral on the left side reduces to $u(t)$

Figure 5: Response to an arbitrary input (3)

The Convolution Integral

The integral

$$\int_{-\infty}^{\infty} u(\tau)h(t-\tau)d\tau$$

or

$$\int_{-\infty}^{\infty} u(t-\tau)h(\tau)d\tau$$

is known as the *convolution integral*; it states that if we know the impulse response of a system, we can compute its time response to any input by using either of the integrals.

The convolution integral is usually written $u(t) * h(t)$ or $h(t) * u(t)$ where the asterisk (*) denotes convolution.

Convolution and State-Space Models

In the previous session, we found that the impulse response of a SISO system (with $d = 0$) was

$$h(t) = \mathbf{C}e^{\mathbf{A}t}\mathbf{B}$$

Therefore, if we know $h(t)$, we can use the convolution integral to compute the response $y(t)$ to any input $u(t)$ using the relation

$$\begin{aligned} h(t) &= \int_{-\infty}^{\infty} \mathbf{C}e^{\mathbf{A}(t-\tau)}\mathbf{B}u(\tau)d\tau \\ h(t) &= \mathbf{C}e^{\mathbf{A}t} \int_{-\infty}^{\infty} e^{-\mathbf{A}\tau}\mathbf{B}u(\tau)d\tau \end{aligned}$$

Graphical Evaluation of the Convolution Integral

Graphical Evaluation of the Convolution Integral

The convolution integral is most conveniently evaluated by a graphical evaluation. The text book gives three examples (6.4-6.6) which we will demonstrate using a [graphical visualization tool](#) developed by Teja Muppirla of the Mathworks.

The tool: [convolutiondemo.m](#) (see [license.txt](#)).

Convolution by Graphical Method - Summary of Steps

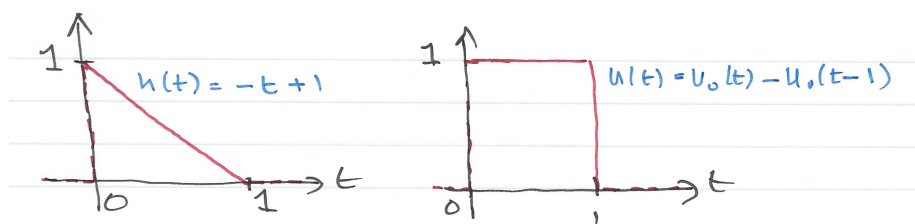
For simplicity, we give the rules for $u(t)$, but the procedure is the same if we reflect and slide $h(t)$

1. Substitute $u(t)$ with $u(\tau)$ – this is a simple change of variable. It doesn't change the definition of $u(t)$.
2. Reflect $u(\tau)$ about the vertical axis to form $u(-\tau)$
3. Slide $u(-\tau)$ to the right a distance t to obtain $u(t - \tau)$
4. Multiply the two signals to obtain the product $u(t - \tau)h(\tau)$
5. Integrate the product over all t from $-\infty$ to ∞ .

Example 1

(This is example 6.4 in the textbook)

The signals $h(t)$ and $u(t)$ are shown below. Compute $h(t) * u(t)$ using the graphical technique.



Prepare for convolutiondemo

To prepare this problem for evaluation in the `convolutiondemo` tool, we need to determine the Laplace Transforms of $h(t)$ and $u(t)$.

$h(t)$

The signal $h(t)$ is the straight line $f(t) = -t + 1$ but this is defined only between $t = 0$ and $t = 1$. We thus need to gate the function by multiplying it by $u_0(t) - u_0(t - 1)$ as illustrated below:

Thus

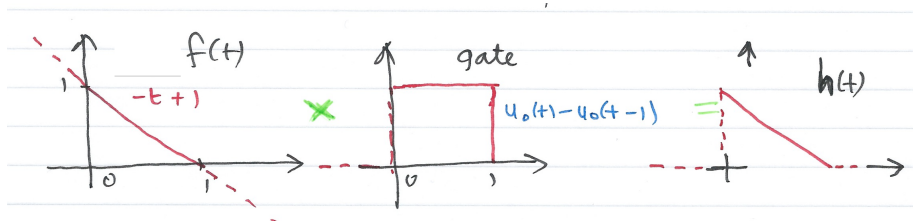


Figure 6: Gating $f(t)$ with $u_0(t) - u_0(t - 1)$ to get $h(t)$

$$\begin{aligned} h(t) &= (-t + 1)(u_0(t) - u_0(t - 1)) \\ &= (-t + 1)u_0(t) - (-(t - 1)u_0(t - 1)) \\ &= -tu_0(t) + u_0(t) + (t - 1)u_0(t - 1) \Leftrightarrow H(s) = -\frac{1}{s^2} + \frac{1}{s} + \frac{e^{-s}}{s^2} \end{aligned}$$

$$H(s) = \frac{s^2 + e^{-s} - 1}{s^2}$$

u(t)

The input $u(t)$ is the gating function:

$$u(t) = u_0(t) - u_0(t - 1)$$

so

$$U(s) = \frac{1}{s} - \frac{e^{-s}}{s} = \frac{1 - e^{-s}}{s}$$

convolutiondemo settings

- Let $g = (1 - \exp(-s))/s$
- Let $h = (s + \exp(-s) - 1)/s^2$
- Set range $-2 < \tau < 2$

Summary of result

1. For $t < 0$: $u(t - \tau)h(\tau) = 0$
2. For $t = 0$: $u(t - \tau) = u(-\tau)$ and $u(-\tau)h(\tau) = 0$
3. For $0 < t \leq 1$: $h * u = \int_0^t (1)(-\tau + 1)d\tau = \tau - \tau^2/2 \Big|_0^t = t - t^2/2$
4. For $1 < t \leq 2$: $h * u = \int_{t-1}^1 (-\tau + 1)d\tau = \tau - \tau^2/2 \Big|_{t-1}^1 = t^2/2 - 2t + 2$
5. For $2 \leq t$: $u(t - \tau)h(\tau) = 0$

Example 2

This is example 6.5 from the text book.

$$h(t) = e^{-t}$$

$$u(t) = u_0(t) - u_0(t - 1)$$

$$y(t) = \begin{cases} 0 & : t \leq 0 \\ 1 - e^{-t} & : 0 < t \leq 1 \\ e^{-t}(e - 1) & : 1 < t \leq 2 \\ 0 & : 2 \leq t \end{cases}$$

Example 3

This is example 6.6 from the text book.

$$h(t) = 2(u_0(t) - u_0(t - 1))$$

$$u(t) = u_0(t) - u_0(t - 2)$$

$$y(t) = \begin{cases} 0 & : t \leq 0 \\ 2t & : 0 < t \leq 1 \\ 2 & : 1 < t \leq 2 \\ -2t + 6 & : 2 < t \leq 3 \\ 0 & : 3 \leq t \end{cases}$$

System Response by Convolution

Example 4

This is example 6.7 from the textbook.

For the circuit shown below, use the convolution integral to find the capacitor voltage when the input is the unit step function $u_0(t)$ and $v_c(0^-) = 0$

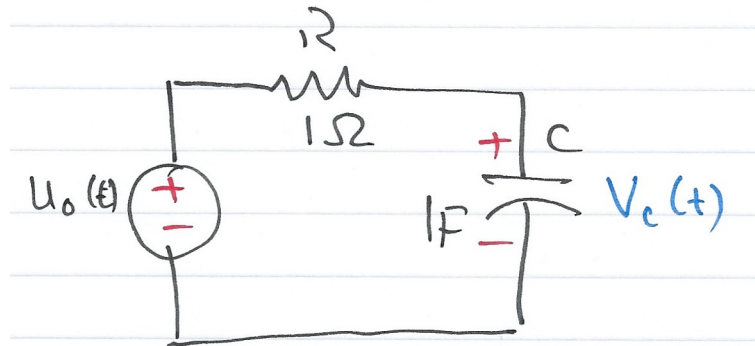


Figure 7: Example 4

Solution

$$h(t) = \frac{1}{RC} e^{-t/RC} u_0(t)$$

which when $C = 1 \text{ F}$ and $R = 1 \Omega$ reduces to

$$h(t) = e^{-t} u_0(t)$$

It is relatively straight forward to show that

$$y(t) = (1 - e^{-t}) u_0(t)$$

System Response by Laplace

System Response by Laplace

In the discussion of Laplace, we stated that

$$\mathcal{L}\{f(t) * g(t)\} = F(s)G(s)$$

We can use this property to make the solution of convolution problems even simpler.

Example 5

Solve Example 4 using Laplace.

Solution

$$h(t) = e^t u_0(t) \Leftrightarrow H(s) = \frac{1}{s+1}$$

$$u(t) = u_0(t) \Leftrightarrow U(s) = \frac{1}{s}$$

$$y(t) = h(t) * u(t) \Leftrightarrow Y(s) = H(s)U(s) = \left(\frac{1}{s}\right) \times \left(\frac{1}{s+1}\right)$$

By PFE

$$Y(s) = \frac{r_1}{s} + \frac{r_2}{s+1}$$

The residues are $r_1 = 1$, $r_2 = -1$, so

$$Y(s) = \frac{1}{s} - \frac{1}{s+1} \Leftrightarrow y(t) = (1 - e^{-t}) u_0(t)$$

Impulse Response and Transfer Functions

A consequence of Laplace is that the transform of the impulse response of a transfer function $G(s)$ is given by the transfer function itself.

$$y(t) = g(t) * \delta(t) \Leftrightarrow Y(s) = G(s).1 = G(s)$$

Thus the Laplace transform of any system subject to an input $u(t)$ is simply

$$Y(s) = G(s)U(s)$$

and

$$y(t) = \mathcal{L}^{-1} \{G(s)U(s)\}$$

Using partial fraction expansion (See lecture on the Inverse-Laplace transform) and transform tables, solution of a convolution problem by Laplace is usually simpler than using the convolution integral directly.

And if the system is particularly complex we can always fall back on the State-Space solution:

$$y(t) = \mathbf{C}e^{\mathbf{A}t} \int_0^t e^{-\mathbf{A}\tau} \mathbf{B}u(\tau) d\tau$$

Homework

You should be able to do any of the questions from Section 6.7 of the textbook.

Lab Work

In the lab we will get you to play with `convolutiondemo`. We will also demonstrate that the solution of the examples in this presentation can readily be solved using Laplace.