

# The Impulse Response and Convolution (Part 1)

# Scope and Background Reading

This session is an introduction to the impulse response of a system and time convolution. Together, these can be used to determine a Linear Time Invariant (LTI) system's time response to any signal.

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.

## *Today*

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

## *Next Session*

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

# The Impulse Response of a System in Time Domain

# The Impulse Response of a System in Time Domain

In the last session we showed that if the state-space model of a SISO system was:

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \mathbf{B}u \\ y &= \mathbf{C}\mathbf{x} + du\end{aligned}$$

the state response would be

$$\mathbf{x}(t) = e^{\mathbf{A}t}\mathbf{x}_0 + \int_0^t e^{\mathbf{A}(t-\tau)}\mathbf{B}u(\tau)d\tau$$

which for our later convenience can be rewritten

$$\mathbf{x}(t) = e^{\mathbf{A}t}\mathbf{x}_0 + e^{\mathbf{A}t} \int_0^t e^{-\mathbf{A}\tau}\mathbf{B}u(\tau)d\tau$$

## Impulse response (1)

If we assume zero initial conditions  $\mathbf{x}_0 = \mathbf{0}$  and  $u(t) = \delta(t)$  (Matlab `dirac`), then the state-reponse to an impulse input is:

$$\mathbf{x}(t) = e^{\mathbf{A}t} \int_0^t e^{-\mathbf{A}\tau} \mathbf{B} \delta(\tau) d\tau$$

Using the *sifting property* of the delta function

$$\int_{-\infty}^{\infty} f(t) \delta(\tau) d\tau = f(0)$$

then

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

so, the impulse response is:

$$y(t) = \mathbf{C}e^{\mathbf{A}t}\mathbf{B} + d\delta(t)$$

## Impulse response (2)

In most systems that you will encounter on this course the scalar quantity  $d = 0$  so the impulse response, which we denote as  $h(t)$ , is

$$h(t) = \mathbf{C}e^{\mathbf{A}t}\mathbf{B}u_0(t)$$

where the unit step function  $u_0(t)$  has been included to indicate that the impulse response is only defined for  $t > 0$ .

## Example 1

Compute the impulse response of the series RC circuit shown below in terms of the constants  $R$  and  $C$ , where the response is considered to be the voltage across the capacitor, and  $v_c(0^-) = 0$ . Then, compute the current through the capacitor.

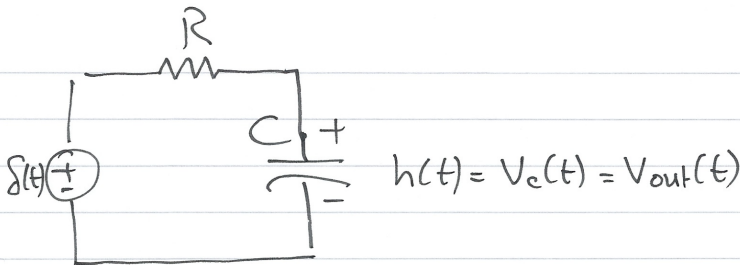


Figure 1: Example 1



## Example 2

In the RLC circuit shown below, compute the impulse response  $h(t) = v_c(t)$  given that the initial conditions are zero, that is  $i_L(0^-) = 0$  and  $V_c(0^-) = 0$ .

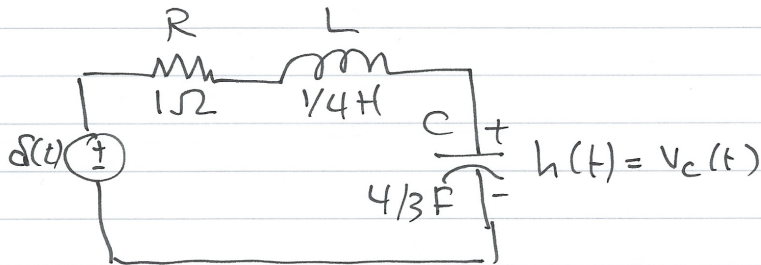


Figure 2: Example 2

## Solution

We tackled this problem as Example 6 in the previous session and found that:

$$\mathbf{B} = \begin{bmatrix} 4 \\ 0 \end{bmatrix}$$
$$e^{\mathbf{A}t} = \begin{bmatrix} -\frac{1}{2}e^{-t} + \frac{3}{2}e^{-3t} & -2e^{-t} + 2e^{-3t} \\ \frac{3}{8}e^{-t} + \frac{3}{8}e^{-3t} & \frac{3}{2}e^{-t} - \frac{1}{2}e^{-3t} \end{bmatrix}$$

so the impulse response of the state variables is:

$$\begin{aligned} \mathbf{x}(t) &= e^{\mathbf{A}t} \mathbf{B} u_0(t) = \begin{bmatrix} -\frac{1}{2}e^{-t} + \frac{3}{2}e^{-3t} & -2e^{-t} + 2e^{-3t} \\ \frac{3}{8}e^{-t} + \frac{3}{8}e^{-3t} & \frac{3}{2}e^{-t} - \frac{1}{2}e^{-3t} \end{bmatrix} \begin{bmatrix} 4 \\ 0 \end{bmatrix} u_0(t) \\ &= \begin{bmatrix} -2e^{-t} + 6e^{-3t} \\ \frac{3}{2}e^{-t} + \frac{3}{2}e^{-3t} \end{bmatrix} u_0(t) \end{aligned}$$

## Impulse response

In Example 6 in the previous session, we defined  $x_1 = i_L$  and  $x_2 = v_c$  so if we want the circuit output to be the capacitor voltage, the output vector  $\mathbf{C}$  will be

$$\mathbf{C} = \begin{bmatrix} 0 & 1 \end{bmatrix}$$

so

$$\begin{aligned} h(t) = y(t) = v_c(t) &= \mathbf{C}e^{\mathbf{A}t}\mathbf{B}u_0(t) \\ &= \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} -2e^{-t} + 6e^{-3t} \\ \frac{3}{2}e^{-t} + \frac{3}{2}e^{-3t} \end{bmatrix} u_0(t) \\ &= \left( \frac{3}{2}e^{-t} + \frac{3}{2}e^{-3t} \right) u_0(t) = \frac{3}{2} (e^{-t} + e^{-3t}) u_0(t) \end{aligned}$$

## Even and Odd Functions of Time

# Even and Odd Functions of Time

(\*\* This should be revision! \*\*)

# Why do we care?

We need to be reminded of *even* and *odd* functions so that we can develop the idea of *time convolution* which is a means of determining the time response of any system for which we know its *impulse response* to any signal.

The development requires us to find out if the Dirac delta function ( $\delta(t)$ ) is an *even* or an *odd* function of time.

# Even Functions of Time

A function  $f(t)$  is said to be an *even function* of time if the following relation holds

$$f(-t) = f(t)$$

that is, if we replace  $t$  with  $-t$  the function  $f(t)$  does not change.

Polynomials with even exponents only, and with or without constants, are even functions. For example:

$$\cos t = 1 - \frac{t^2}{2!} + \frac{t^4}{4!} - \frac{t^6}{6!} + \dots$$

is even.

## Other Examples of Even Functions

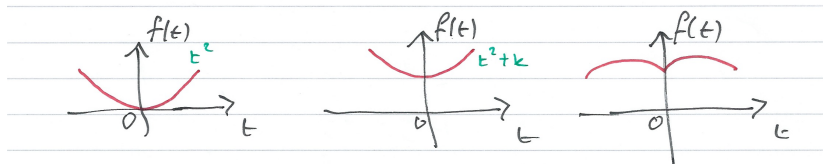


Figure 3: Even functions



# Odd Functions of Time

A function  $f(t)$  is said to be an *odd function* of time if the following relation holds

$$-f(-t) = f(t)$$

that is, if we replace  $t$  with  $-t$ , we obtain the negative of the function  $f(t)$ .

Polynomials with odd exponents only, and no constants, are odd functions. For example:

$$\sin t = t - \frac{t^3}{3!} + \frac{t^5}{5!} - \frac{t^7}{7!} + \dots$$

is odd.

## Other Examples of Odd Functions

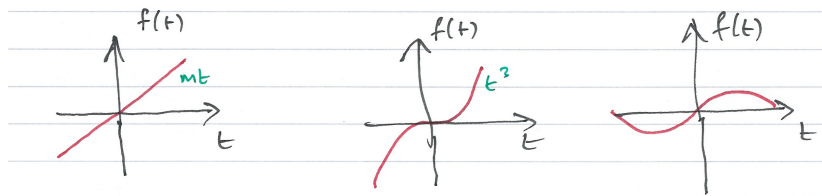


Figure 4: Examples of odd functions

# Observations

- ▶ For odd functions  $f(0) = 0$ .
- ▶ If  $f(0) = 0$  we should not conclude that  $f(t)$  is an odd function. *c.f.*  $f(t) = t^2$  is even, not odd.
- ▶ The product of *two even* or *two odd* functions is an even function.
- ▶ The product of an even and an odd function, is an odd function.

In the following  $f_e(t)$  will denote an even function and  $f_o(t)$  an odd function.

# Time integrals of even and odd functions

For an even function  $f_e(t)$

$$\int_{-T}^T f_e(t) dt = 2 \int_0^T f_e(t) dt$$

For an odd function  $f_o(t)$

$$\int_{-T}^T f_o(t) dt = 0$$

# Even/Odd Representation of an Arbitrary Function

A function  $f(t)$  that is neither even nor odd can be represented as an even function by use of:

$$f_e(t) = \frac{1}{2} [f(t) + f(-t)]$$

or as an odd function by use of:

$$f_o(t) = \frac{1}{2} [f(t) - f(-t)]$$

Adding these together, an arbitrary signal can be represented as

$$f(t) = f_e(t) + f_o(t)$$

That is, any function of time can be expressed as the sum of an even and an odd function.

## Example 3

Is the Dirac delta  $\delta(t)$  an even or an odd function of time?

## Solution

Let  $f(t)$  be an arbitrary function of time that is continuous at  $t = t_0$ . Then by the sifting property of the delta function

$$\int_{-\infty}^{\infty} f(t)\delta(t - t_0)dt = f(t_0)$$

and for  $t_0 = 0$

$$\int_{-\infty}^{\infty} f(t)\delta(t)dt = f(0)$$

Also for an even function  $f_e(t)$

$$\int_{-\infty}^{\infty} f_e(t) \delta(t) dt = f_e(0)$$

and for an odd function  $f_o(t)$

$$\int_{-\infty}^{\infty} f_o(t) \delta(t) dt = f_o(0)$$



## Even or odd?

An odd function  $f_o(t)$  evaluated at  $t = 0$  is zero, that is  $f_o(0) = 0$ .

Hence

$$\int_{-\infty}^{\infty} f_o(t)\delta(t)dt = f_o(0) = 0$$

Hence the product  $f_o(t)\delta(t)$  is odd function of  $t$ .

Since  $f_o(t)$  is odd,  $\delta(t)$  must be even because only an *even* function multiplied by an *odd* function can result in an *odd* function.

(Even times even or odd times odd produces an even function. See earlier slide)

Is the Dirac delta  $\delta(t)$  an even or an odd function of time?

$\delta(t)$  is an *even* function.

This will be useful to us later.

# Next Time

We will conclude our discussion of *Time Convolution* by presenting:

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

# Homework

You should be able to do Question 1 from Section 6.7 of the textbook.

If you want to refresh your knowledge of even and odd functions, Chapter 1 of Schaum's Outline on Signals and Systems (Hsu, 2nd Ed.) has some examples. For example see Solved Problems 1.5–1.8 and Supplementary Problems 1.48–1.50\$.

# Lab Work

In the lab, a week on Friday, we will demonstrate the solution of Examples 1 and 2 in Matlab.