CHBE320 LECTURE V
LAPLACE TRANSFORM AND TRANSFER FUNCTION

Professor Dae Ryook Yang

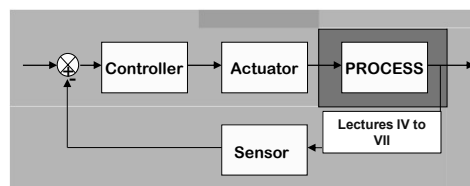### Fall 2021
Dept. of Chemical and Biological Engineering
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Road Map of the Lecture V

- **Laplace Transform and Transfer functions**
    - **Definition of Laplace transform**
    - **Properties of Laplace transform**
    - **Inverse Laplace transform**
    - **Definition of transfer function**
    - **How to get the transfer functions**
    - **Properties of transfer function**

SOLUTION OF LINEAR ODE

- **1st-order linear ODE**
  - **Integrating factor:** For $\frac{dx}{dt} + a(t)x = f(t)$, I.F. $= \exp(\int a(t)dt)$

  $[xe^{\int a(t)dt}]' = f(t)e^{\int a(t)dt}$ $\longrightarrow$ $x(t) = [\int f(t)e^{\int a(t)dt}\, dt + C]e^{-\int a(t)dt}$

- **High-order linear ODE with constant coeffs.**
  - **Modes: roots of characteristic equation**

  For $a_2 x'' + a_1 x' + a_0 x = f(t)$,

  $a_2 p^2 + a_1 p + a_0 = a_2(p - p_1)(p - p_2) = 0$

  - **Depending on the roots, modes are**
    - **Distinct roots:** $(e^{-p_1 t}, e^{-p_2 t})$
    - **Double roots:** $(e^{-p_1 t}, te^{-p_1 t})$
   - **Imaginary roots:** $(e^{-\alpha t}\cos\beta t, e^{-\alpha}\sin\beta t)$ $\longrightarrow$ **Solution is a linear combination of modes and the coefficients are decided by the initial conditions**.

- **Many other techniques for different cases**

LAPLACE TRANSFORM FOR LINEAR ODE AND PDE

- **Laplace Transform**
  - **Not in time domain, rather in frequency domain**
  - **Derivatives and integral become some operators.**
  - **ODE is converted into algebraic equation**
  - **PDE is converted into ODE in spatial coordinate**
  - **Need inverse transform to recover time-domain solution**

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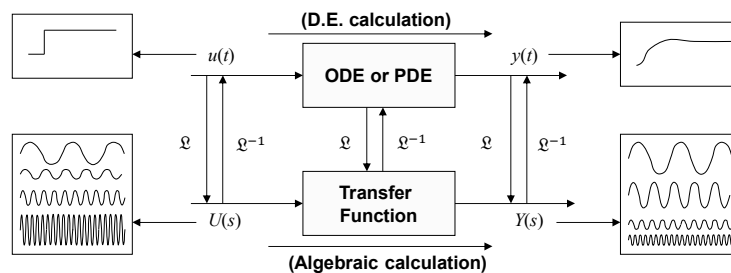
DEFINITION OF LAPLACE TRANSFORM

- **Definition**

$$F(s) = \mathfrak{L}\{f(t)\} \triangleq \int_0^\infty f(t)e^{-s}\, dt$$

  – *F(s)* is called *Laplace transform* of *f(t)*.
  – *f(t)* must be piecewise continuous.
  – *F(s)* contains no information on *f(t)* for *t* < 0.
  – The past information on *f(t)* (for *t* < 0) is irrelevant.
  – The *s* is a complex variable called "*Laplace transform variable*"
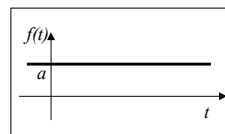
- **Inverse Laplace transform**

$$f(t) = \mathfrak{L}^{-1}\{F(s)\}$$

  – $\mathfrak{L}$ and $\mathfrak{L}^{-1}$ are linear. $\mathfrak{L}\{af_1(t) + bf_2(t)\} = aF_1(s) + bF_2(s)$

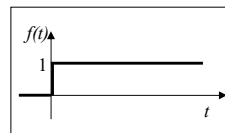# LAPLACE TRANSFORM OF FUNCTIONS

- **Constant function,** *a*

$$\mathfrak{L}\{a\} = \int_0^\infty ae^{-st}dt = -\frac{a}{s}e^{-st}\Big|_0^\infty = 0 - \left(-\frac{a}{s}\right) = \frac{a}{s}$$
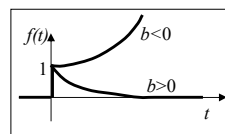
- **Step function,** S(*t*)

$$f(t) = S(t) = \begin{cases} 1 & \text{for } t \geq 0 \\ 0 & \text{for } t < 0 \end{cases}$$

$$\mathfrak{L}\{S(t)\} = \int_0^\infty e^{-st}dt = -\frac{1}{s}e^{-st}\Big|_0^\infty = 0 - \left(-\frac{1}{s}\right) = \frac{1}{s}$$
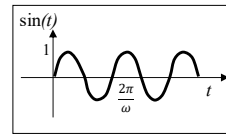
- **Exponential function,** e^{-bt}

$$\mathfrak{L}\{e^{-bt}\} = \int_0^\infty e^{-bt}e^{-st}dt = \frac{-1}{s+b}e^{-(b+s)t}\Big|_0^\infty = \frac{1}{s+b}$$

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- **Trigonometric functions**
  - **Euler's Identity:** $e^{j\omega t} \triangleq \cos \omega t + j \sin \omega t$

$$\cos \omega t = \frac{1}{2}\left(e^{j\omega t} + e^{-j\omega}\right) \qquad \sin \omega t = \frac{1}{2j}\left(e^{j\omega t} - e^{-j\omega}\right)$$

$$\mathcal{L}\{\sin \omega t\} = \mathcal{L}\left\{\frac{1}{2j}e^{j\omega t}\right\} - \mathcal{L}\left\{\frac{1}{2j}e^{-j\omega t}\right\} = \frac{1}{2j}\left(\frac{1}{s - j\omega} - \frac{1}{s + j\omega}\right) = \frac{\omega}{s^2 + \omega^2}$$
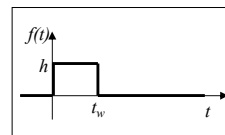
$$\mathcal{L}\{\cos \omega t\} = \mathcal{L}\left\{\frac{1}{2}e^{j\omega t}\right\} + \mathcal{L}\left\{\frac{1}{2}e^{-j\omega t}\right\} = \frac{1}{2}\left(\frac{1}{s - j\omega} + \frac{1}{s + j\omega}\right) = \frac{s}{s^2 + \omega^2}$$
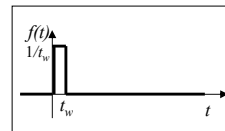
- **Rectangular pulse, $\mathrm{P}(t)$**

$$f(t) = \mathrm{P}(t) = \begin{cases} 0 & \text{for } t > t_w \\ h & \text{for } t_w \geq t \geq 0 \\ 0 & \text{for } t < 0 \end{cases}$$

$$\mathcal{L}\{\mathrm{P}(t)\} = \int_0^{t_w} h e^{-st} dt = -\frac{h}{s}e^{-st}\Big|_0^{t_w} = \frac{h}{s}(1 - e^{-t_w s})$$

- **Impulse function,** $\delta(t)$

$$f(t) = \delta(t) = \lim_{t_w \to 0} \begin{cases} 0 & \text{for } t > t_w \\ 1/t_w & \text{for } t_w \geq t \geq 0 \\ 0 & \text{for } t < 0 \end{cases}$$

$$\mathcal{L}\{\delta(t)\} = \lim_{t_w \to 0} \int_0^{t_w} \frac{1}{t_w} e^{-st} dt = \lim_{t_w \to 0} \frac{1}{t_w s}(1 - e^{-t_w s}) = 1$$

$$\left(\text{L'Hospital's rule: } \lim_{t \to 0} \frac{f(t)}{g(t)} = \lim_{t \to 0} \frac{f'(t)}{g'(t)}\right)$$

- **Ramp function,** t

$$\mathcal{L}\{t\} = \int_0^\infty t e^{-st} dt$$

$$= \frac{t}{-s}e^{-st}\Big|_0^\infty - \int_0^\infty \frac{e^{-st}}{-s} dt = \frac{1}{s}\int_0^\infty e^{-st} dt = \frac{1}{s^2}$$
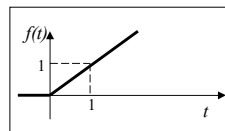
$$\left(\text{Integration by part: } \int_0^\infty f' \cdot g\, dt = f \cdot g\Big|_0^\infty - \int_0^\infty f \cdot g'\, dt\right)$$

- **Refer the Table 3.1 (Seborg et al.) for other functions**

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Table 3.1   Laplace Transforms for Various Time-Domain Functions[a]

	$f(t)$	$F(s)$
1.	$\delta(t)$ (unit impulse)	1
2.	$S(t)$ (unit step)	$\dfrac{1}{s}$
3.	t (ramp)	$\dfrac{1}{s^2}$
4.	t^{n-1}	$\dfrac{(n-1)!}{s^n}$
5.	e^{-bt}	$\dfrac{1}{s+b}$
6.	$\dfrac{1}{\tau}e^{-t/\tau}$	$\dfrac{1}{\tau s+1}$
7.	$\dfrac{t^{n-1}e^{-bt}}{(n-1)!}$ $(n>0)$	$\dfrac{1}{(s+b)^n}$
8.	$\dfrac{1}{\tau^n(n-1)!}\,t^{n-1}e^{-t/\tau}$	$\dfrac{1}{(\tau s+1)^n}$
9.	$\dfrac{1}{b_1-b_2}\left(e^{-b_2 t}-e^{-b_1 t}\right)$	$\dfrac{1}{(s+b_1)(s+b_2)}$
10.	$\dfrac{1}{\tau_1-\tau_2}\left(e^{-t/\tau_1}-e^{-t/\tau_2}\right)$	$\dfrac{1}{(\tau_1 s+1)(\tau_2 s+1)}$
11.	$\dfrac{b_3-b_1}{b_2-b_1}e^{-b_1 t}+\dfrac{b_3-b_2}{b_1-b_2}e^{-b_2 t}$	$\dfrac{s+b_3}{(s+b_1)(s+b_2)}$
12.	$\dfrac{1}{\tau_1-\tau_2}\dfrac{\tau_3-\tau_1}{\tau_1}e^{-t/\tau_1}+\dfrac{1}{\tau_2-\tau_1}\dfrac{\tau_2-\tau_3}{\tau_2}e^{-t/\tau_2}$	$\dfrac{\tau_3 s+1}{(\tau_1 s+1)(\tau_2 s+1)}$
13.	$1-e^{-t/\tau}$	$\dfrac{1}{s(\tau s+1)}$
14.	$\sin \omega t$	$\dfrac{\omega}{s^2+\omega^2}$

Table 3.1 (*Continued*)

	$f(t)$	$F(s)$
15.	$\cos \omega t$	$\dfrac{s}{s^2+\omega^2}$
16.	$\sin(\omega t+\phi)$	$\dfrac{\omega\cos\phi+s\sin\phi}{s^2+\omega^2}$
17.	$e^{-bt}\sin\omega t$ $\left.\right\}$ b,ω real	$\dfrac{\omega}{(s+b)^2+\omega^2}$
18.	$e^{-bt}\cos\omega t$	$\dfrac{s+b}{(s+b)^2+\omega^2}$
19.	$\dfrac{1}{\tau\sqrt{1-\zeta^2}}e^{-\zeta t/\tau}\sin\left(\sqrt{1-\zeta^2}\,t/\tau\right)$ $(0\le|\zeta|<1)$	$\dfrac{1}{\tau^2 s^2+2\zeta\tau s+1}$
20.	$1+\dfrac{1}{\tau_2-\tau_1}\left(\tau_1 e^{-t/\tau_1}-\tau_2 e^{-t/\tau_2}\right)$ $(\tau_1\ne\tau_2)$	$\dfrac{1}{s(\tau_1 s+1)(\tau_2 s+1)}$
21.	$1-\dfrac{1}{\sqrt{1-\zeta^2}}e^{-\zeta t/\tau}\sin\left[\sqrt{1-\zeta^2}\,t/\tau+\psi\right]$ $\psi=\tan^{-1}\dfrac{\sqrt{1-\zeta^2}}{\zeta}$ $(0\le|\zeta|<1)$	$\dfrac{1}{s(\tau^2 s^2+2\zeta\tau s+1)}$
22.	$1-e^{-\zeta t/\tau}\left[\cos\left(\sqrt{1-\zeta^2}\,t/\tau\right)\right.$ $\left.+\dfrac{\zeta}{\sqrt{1-\zeta^2}}\sin\left(\sqrt{1-\zeta^2}\,t/\tau\right)\right]$ $(0\le|\zeta|<1)$	$\dfrac{1}{s(\tau^2 s^2+2\zeta\tau s+1)}$
23.	$1+\dfrac{\tau_3-\tau_1}{\tau_1-\tau_2}e^{-t/\tau_1}+\dfrac{\tau_3-\tau_2}{\tau_2-\tau_1}e^{-t/\tau_2}$ $(\tau_1\ne\tau_2)$	$\dfrac{\tau_3 s+1}{s(\tau_1 s+1)(\tau_2 s+1)}$
24.	$\dfrac{df}{dt}$	$sF(s)-f(0)$
25.	$\dfrac{d^n f}{dt^n}$	$s^n F(s)-s^{n-1}f(0)-s^{n-2}f^{(1)}(0)-\cdots$ $-sf^{(n-2)}(0)-f^{(n-1)}(0)$

[a]Note that $f(t)$ and $F(s)$ are defined for $t\ge 0$ only.

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PROPERTIES OF LAPLACE TRANSFORM

- **Differentiation**

$$\mathfrak{L}\left\{\frac{df}{dt}\right\} = \int_0^\infty f' \cdot e^{-s}\, dt = f(t)e^{-st}\Big|_0^\infty - \int_0^\infty f \cdot (-s)e^{-st}dt \quad (\text{by } i.b.p.)$$
$$= s\int_0^\infty f \cdot e^{-s}\, dt - f(0) = sF(s) - f(0)$$

$$\mathfrak{L}\left\{\frac{d^2 f}{dt^2}\right\} = \int_0^\infty f'' \cdot e^{-st}dt = f(t)'e^{-s}\Big|_0^\infty - \int_0^\infty f' \cdot (-s)e^{-s}\, dt = s\int_0^\infty f' \cdot e^{-st}dt - f'(0)$$
$$= s(sF(s) - f(0)) - f'(0) = s^2 F(s) - sf(0) - f'(0)$$

$$\vdots$$

$$\mathfrak{L}\left\{\frac{d^n f}{dt^n}\right\} = \int_0^\infty f^{(n)} \cdot e^{-st}dt = f(t)^{(n-1)}e^{-s}\Big|_0^\infty - \int_0^\infty f^{(n-1)} \cdot (-s)e^{-st}dt$$
$$= s\int_0^\infty f^{(n-1)} \cdot e^{-st}dt - f^{(n-1)}(0) = s\left(\mathfrak{L}\left\{\frac{d^{n-1}f}{dt^{n-1}}\right\}\right) - f^{(n-1)}(0)$$
$$= s^n F(s) - s^{n-1}f(0) - \cdots - sf^{(n-2)}(0) - f^{(n-1)}(0)$$

- **If** $f(0) = f'(0) = f''(0) = \ldots = f^{(n-1)}(0) = 0$,
  - **Initial condition effects are vanished.**
  - **It is very convenient to use deviation variables so that all the effects of initial condition vanish.**

$$\mathfrak{L}\left\{\frac{df}{dt}\right\} = sF(s)$$
$$\mathfrak{L}\left\{\frac{d^2 f}{dt^2}\right\} = s^2 F(s)$$
$$\vdots$$
$$\mathfrak{L}\left\{\frac{d^n f}{dt^n}\right\} = s^n F(s)$$

- **Transforms of linear differential equations.**

$$y(t) \xrightarrow{\mathfrak{L}} Y(s), \qquad u(t) \xrightarrow{\mathfrak{L}} U(s)$$
$$\frac{dy(t)}{dt} \xrightarrow{\mathfrak{L}} sY(s) \quad (\text{if } y(0) = 0)$$

$$\tau\frac{dy(t)}{dt} = -y(t) + Ku(t) \quad (y(0) = 0) \xrightarrow{\mathfrak{L}} (\tau s + 1)Y(s) = KU(s)$$

$$\frac{\partial T_L}{\partial t} = -v\frac{\partial T_L}{\partial z} + \frac{1}{\tau_{HL}}(T_w - T_L) \xrightarrow{\mathfrak{L}} \tau_{HL}v\frac{\partial \tilde{T}_L(s)}{\partial z} + (\tau_{HL}s + 1)\tilde{T}_L(s) = \tilde{T}_w(s)$$
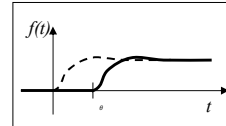
- **Integration**

$$\mathcal{L}\left\{\int_0^t f(\xi)d\xi\right\} = \int_0^\infty \left(\int_0^t f(\xi)d\xi\right)e^{-st}dt$$

$$= \frac{e^{-st}}{-s}\int_0^t f(\xi)d\xi\Big|_0^\infty + \frac{1}{s}\int_0^\infty f \cdot e^{-st}dt = \frac{F(s)}{s} \qquad (\text{by } i.b.p.)$$

$$\left(\text{Leibniz rule: } \frac{d}{dt}\int_{a(t)}^{b(t)} f(\tau)d\tau = f(b(t))\frac{db(t)}{dt} - f(a(t))\frac{da(t)}{dt}\right)$$

- **Time delay (Translation in time)**

$$f(t)\xrightarrow{+\theta \text{ in } t} f(t-\theta)\,S(t-\theta)$$

$$\mathcal{L}\{f(t-\theta)\,S(t-\theta)\} = \int_\theta^\infty f(t-\theta)e^{-st}dt = \int_0^\infty f(\tau)e^{-s(\tau+\theta)}d\tau \quad (\text{let } \tau = t-\theta)$$

$$= e^{-\theta s}\int_0^\infty f(\tau)e^{-\tau s}d\tau = e^{-\theta s}F(s)$$

- **Derivative of Laplace transform**

$$\frac{dF(s)}{ds} = \frac{d}{ds}\int_0^\infty f \cdot e^{-st}dt = \int_0^\infty f \cdot \frac{d}{ds}e^{-st}dt = \int_0^\infty (-t \cdot f)e^{-st}dt = \mathcal{L}[-t \cdot f(t)]$$

- **Final value theorem**
  - **From the LT of differentiation, as s approaches to zero**

$$\lim_{s\to 0}\int_0^\infty \frac{df}{dt}\cdot e^{-s}\ dt = \int_0^\infty \frac{df}{dt}\cdot \lim_{s\to 0}e^{-s}\ dt = \lim_{s\to 0}[sF(s)-f(0)]$$

$$\int_0^\infty \frac{df}{dt}\,dt = f(\infty)-f(0) = \lim_{s\to 0}s\,F(s)-f(0) \Rightarrow \boxed{f(\infty)=\lim_{s\to 0}s\,F(s)}$$

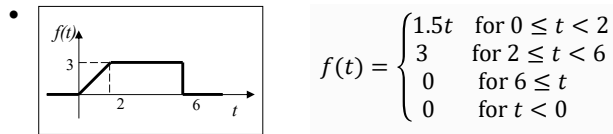 - **Limitation:** $f(\infty)$ **has to exist. If it diverges or oscillates, this theorem is not valid.**

- **Initial value theorem**
  - **From the LT of differentiation, as s approaches to infinity**

$$\lim_{s\to\infty}\int_0^\infty \frac{df}{dt}\cdot e^{-s}\ dt = \lim_{s\to\infty}[sF(s)-f(0)]$$

$$\lim_{s\to\infty}\int_0^\infty \frac{df}{dt}e^{-st}dt = 0 = \lim_{s\to\infty}s\,F(s)-f(0) \Rightarrow \boxed{f(0)=\lim_{s\to\infty}s\,F(s)}$$

EXAMPLE ON LAPLACE TRANSFORM (1)

$$f(t) = \begin{cases} 1.5t & \text{for } 0 \le t < 2 \\ 3 & \text{for } 2 \le t < 6 \\ 0 & \text{for } 6 \le t \\ 0 & \text{for } t < 0 \end{cases}$$

$$f(t) = 1.5t\, S(t) - 1.5(t-2)\, S(t-2) - 3\, S(t-6)$$

$$\therefore F(s) = \mathcal{L}\{f(t)\} = \frac{1.5}{s^2}(1 - e^{-2s}) - \frac{3}{s}e^{-6s}$$

- For $F(s) = \dfrac{2}{s-5}$, find $f(0)$ and $f(\infty)$.

  – **Using the initial and final value theorems**

  $$f(0) = \lim_{s \to \infty} s\, F(s) = \lim_{s \to \infty} \frac{2s}{s-5} = 2 \qquad f(\infty) = \lim_{s \to 0} s\, F(s) = \lim_{s \to 0} \frac{2s}{s-5} = 0$$

  – **But the final value theorem is not valid because**

  $$\lim_{t \to \infty} f(t) = \lim_{t \to \infty} 2\, e^{5t}$$

EXAMPLE ON LAPLACE TRANSFORM (2)

- **What is the final value of the following system?**

  $$x'' + x' + x = \sin t\,;\ x(0) = x'(0) = 0$$

  $$\Rightarrow s^2 X(s) + s X(s) + X = \frac{1}{s^2 + 1} \Rightarrow x(s) = \frac{1}{(s^2 + 1)(s^2 + s + 1)}$$

  $$x(\infty) = \lim_{s \to 0} \frac{s}{(s^2 + 1)(s^2 + s + 1)} = 0$$

  – **Actually, $x(\infty)$ cannot be defined due to sin t term.**

- **Find the Laplace transform for $(t \sin \omega t)$?**

  From $\dfrac{dF(s)}{ds} = \mathcal{L}[-t \cdot f(t)]$

  $$\mathcal{L}[t \cdot \sin \omega t] = -\frac{d}{ds}\left[\frac{\omega}{s^2 + \omega^2}\right] = \frac{2\omega s}{(s^2 + \omega^2)^2}$$

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INVERSE LAPLACE TRANSFORM

- **Used to recover the solution in time domain**

$$\boxed{\mathcal{L}^{-1}\{F(s)\} = f(t)}$$

  – **From the table**
  – **By partial fraction expansion**
  – **By inversion using contour integral**

$$f(t) = \mathcal{L}^{-1}\{F(s)\} = \frac{1}{2\pi j} \oint_C e^{st} F(s) ds$$

- **Partial fraction expansion**
  – **After the partial fraction expansion, it requires to know some simple formula of inverse Laplace transform such as**

$$\frac{1}{(\tau s + 1)}, \frac{s}{(s+b)^2 + \omega^2}, \frac{(n-1)!}{s^n}, \frac{e^{-\theta}}{\tau^2 s^2 + 2\zeta\tau s + 1}, \text{ etc.}$$

PARTIAL FRACTION EXPANSION

$$\boxed{F(s) = \frac{N(s)}{D(s)} = \frac{N(s)}{(s+p_1)\cdots(s+p_n)} = \frac{\alpha_1}{(s+p_1)} + \cdots + \frac{\alpha_n}{(s+p_n)}}$$

- **Case I: All p_i's are distinct and real**
  – **By a root-finding technique, find all roots (time-consuming)**
  – **Find the coefficients for each fraction**
    - **Comparison of the coefficients after multiplying the denominator**
    - **Replace some values for s and solve linear algebraic equation**
    - **Use of Heaviside expansion**
      – **Multiply both side by a factor, $(s+p_i)$, and replace s with $-p_i$.**

$$\alpha_i = (s+p_i)\frac{N(s)}{D(s)}\Big|_{s=-p_i}$$

  – **Inverse LT:**

$$f(t) = \alpha_1 e^{-p_1 t} + \alpha_2 e^{-p_2 t} + \cdots + \alpha_n e^{-p_n t}$$

- **Case II: Some roots are repeated**

$$F(s) = \frac{N(s)}{D(s)} = \frac{N(s)}{(s+p)^r} = \frac{b_{r-1}s^{r-1} + \cdots + b_0}{(s+p)^r} = \frac{\alpha_1}{(s+p)} + \cdots + \frac{\alpha_r}{(s+p)^r}$$

  – **Each repeated factors have to be separated first.**
  – **Same methods as Case I can be applied.**
  – **Heaviside expansion for repeated factors**

$$\alpha_{r-i} = \frac{1}{i!}\frac{d^{(i)}}{ds^{(i)}}\left(\frac{N(s)}{D(s)}(s+p)^r\right)\bigg|_{s=-p} \qquad (i = 0, \cdots, r-1)$$

  – **Inverse LT**

$$f(t) = \alpha_1 e^{-p} + \alpha_2 t e^{-pt} + \cdots + \frac{\alpha_r}{(r-1)!}t^{r-1}e^{-p}$$

- **Case III: Some roots are complex**

$$F(s) = \frac{N(s)}{D(s)} = \frac{c_1 s + c_0}{s^2 + d_1 s + d_0} = \frac{\alpha_1(s+b) + \beta_1\omega}{(s+b)^2 + \omega^2}$$

  – **Each repeated factors have to be separated first.**
  – **Then,**

$$\frac{\alpha_1(s+b) + \beta_1\omega}{(s+b)^2 + \omega^2} = \alpha_1\frac{(s+b)}{(s+b)^2 + \omega^2} + \beta_1\frac{\omega}{(s+b)^2 + \omega^2}$$

  where $b = d_1/2,$ $\qquad \omega = \sqrt{d_0 - d_1^2/4}$

  $\qquad \alpha_1 = c_1,$ $\qquad \beta_1 = (c_0 - \alpha_1 b)/\omega$

  – **Inverse LT**

$$f(t) = \alpha_1 e^{-bt}\cos\omega t + \beta_1 e^{-bt}\sin\omega t$$

EXAMPLES ON INVERSE LAPLACE TRANSFORM

- $F(s) = \dfrac{(s+5)}{s(s+1)(s+2)(s+3)} = \dfrac{A}{s} + \dfrac{B}{s+1} + \dfrac{C}{s+2} + \dfrac{D}{s+3}$ (distinct)

  - **Multiply each factor and insert the zero value**

    $\left.\dfrac{(s+5)}{(s+1)(s+2)(s+3)}\right|_{s=0} = \left.\left(A + s\dfrac{B}{s+1} + s\dfrac{C}{s+2} + s\dfrac{D}{s+3}\right)\right|_{s=0} \Rightarrow A = 5/6$

    $\left.\dfrac{(s+5)}{s(s+2)(s+3)}\right|_{s=-1} = \left.\left(\dfrac{A(s+1)}{s} + B + \dfrac{C(s+1)}{s+2} + \dfrac{D(s+1)}{s+3}\right)\right|_{s=-1} \Rightarrow B = -2$

    $\left.\dfrac{(s+5)}{s(s+1)(s+3)}\right|_{s=-2} = \left.\left(\dfrac{A(s+2)}{s} + \dfrac{B(s+2)}{s+1} + C + \dfrac{D(s+2)}{s+3}\right)\right|_{s=-2} \Rightarrow C = 3/2$

    $\left.\dfrac{(s+5)}{s(s+1)(s+2)}\right|_{s=-3} = \left.\left(\dfrac{A(s+3)}{s} + \dfrac{B(s+3)}{s+1} + \dfrac{C(s+3)}{s+2} + D\right)\right|_{s=-3} \Rightarrow D = -1/3$

    $\therefore f(t) = \mathcal{L}^{-1}\{F(s)\} = \dfrac{5}{6} - 2e^{-t} + \dfrac{3}{2}e^{-2} - \dfrac{1}{3}e^{-3}$

- $F(s) = \dfrac{1}{(s+1)^3(s+2)} = \dfrac{As^2 + Bs + C}{(s+1)^3} + \dfrac{D}{(s+2)}$ (repeated)

  $1 = (As^2 + Bs + C)(s+2) + D(s+1)^3$
  $= (A+D)s^3 + (2A+B+3D)s^2 + (2B+C+3D)s + (2C+D)$

  $\therefore A = -D, \qquad 2A+B+3D = 0, \qquad 2B+C+3D = 0, \qquad 2C+D = 1$

  $\Rightarrow A = 1, \qquad B = 1, \qquad C = 1, \qquad D = -1$

  - **Use of Heaviside expansion** $\left.\alpha_{r-i} = \dfrac{1}{i!}\dfrac{d^{(i)}}{ds^{(i)}}\left(\dfrac{N(s)}{D(s)}(s+p)^r\right)\right|_{s=-p}$ $(i = 0, \cdots, r-1)$

  $\dfrac{s^2 + s + 1}{(s+1)^3} = \dfrac{\alpha_1}{(s+1)} + \dfrac{\alpha_2}{(s+1)^2} + \dfrac{\alpha_3}{(s+1)^3}$

  $(i = 0):\ \alpha_3 = \left.(s^2 + s + 1)\right|_{s=-1} = 1$

  $(i = 1):\ \alpha_2 = \left.\dfrac{1}{1!}\dfrac{d}{ds}(s^2 + s + 1)\right|_{s=-1} = -1$

  $(i = 2):\ \alpha_1 = \left.\dfrac{1}{2!}\dfrac{d^2}{ds^2}(s^2 + s + 1)\right|_{s=-1} = 1$

  $\therefore f(t) = \mathcal{L}^{-1}\{F(s)\} = e^{-t} - te^{-t} + \dfrac{1}{2}t^2 e^{-t} - e^{-2t}$

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- $F(s) = \dfrac{(s+1)}{s^2(s^2+4s+5)} = \dfrac{A(s+2)+B}{(s+2)^2+1} + \dfrac{Cs+D}{s^2}$ (complex)

$$s + 1 = A(s+2)s^2 + Bs^2 + (Cs+D)(s^2+4s+5)$$
$$= (A+C)s^3 + (2A+B+4C+D)s^2 + (5C+4D)s + 5D$$

$$\therefore A = -C, \qquad 2A+B+4C+D = 0, \qquad 5C+4D = 1, \qquad 5D = 1$$
$$\Rightarrow A = -1/25, \qquad B = -7/25, \qquad C = 1/25, \qquad D = 1/5$$

$$\frac{A(s+2)+B}{(s+2)^2+1} = -\frac{1}{25}\frac{(s+2)}{(s+2)^2+1} - \frac{7}{25}\frac{B}{(s+2)^2+1}$$

$$\frac{Cs+D}{s^2} = \frac{1}{25}\frac{1}{s} + \frac{1}{5}\frac{1}{s^2}$$

$$\therefore f(t) = \mathcal{L}^{-1}\{F(s)\} = -\frac{1}{25}e^{-2t}\cos t - \frac{7}{25}e^{-2t}\sin t + \frac{1}{25} + \frac{1}{5}t$$

- $F(s) = \dfrac{1+e^{-2}}{(4s+1)(3s+1)} = \left(\dfrac{A}{4s+1} + \dfrac{B}{3s+1}\right)(1+e^{-2s})$ (Time delay)

$$A = 1/(3s+1)\Big|_{s=-1/4} = 4, \qquad B = 1/(4s+1)\Big|_{s=-1/3} = -3$$

$$\therefore f(t) = \mathcal{L}^{-1}\{F(s)\} = \mathcal{L}^{-1}\left\{\frac{4}{4s+1} - \frac{3}{3s+1}\right\} + \mathcal{L}^{-1}\left\{\frac{4e^{-2s}}{4s+1} - \frac{3e^{-2}}{3s+1}\right\}$$
$$= e^{-t/4} - e^{-t/3} + \left(e^{-(t-2)/4} - e^{-(t-2)/3}\right)S(t-2)$$

SOLVING ODE BY LAPLACE TRANSFORM

- **Procedure**

    1. **Given linear ODE with initial condition,**
    2. **Take Laplace transform and solve for output**
    3. **Inverse Laplace transform**

- **Example:** Solve for $5\dfrac{dy}{dt} + 4y = 2;\ y(0) = 1$

$$\mathcal{L}\left\{5\frac{dy}{dt}\right\} + \mathcal{L}\{4y\} = \mathcal{L}\{2\} \ \Rightarrow\ 5(sY(s) - y(0)) + 4Y(s) = \frac{2}{s}$$

$$(5s + 4)Y(s) = \frac{2}{s} + 5 \ \Rightarrow\ Y(s) = \frac{5s + 2}{s(5s + 4)}$$

$$\therefore y(t) = \mathcal{L}^{-1}\{Y(s)\} = \mathcal{L}^{-1}\left\{\frac{0.5}{s} + \frac{2.5}{5s + 4}\right\} = 0.5 + 0.5e^{-0.8t}$$
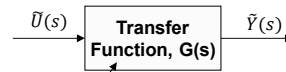
TRANSFER FUNCTION (1)

- **Definition**
    – **An algebraic expression for the dynamic relation between the input and output of the process model**

$$5\frac{dy}{dt} + 4y = u;\ y(0) = 1$$
Let $\tilde{y} = y - 1$ and $\tilde{u} = u - 4$

$$(5s + 4)\tilde{Y}(s) = \tilde{U}(s) \ \Rightarrow\ \frac{\tilde{Y}(s)}{\tilde{U}(s)} = \frac{1}{5s + 4} = \frac{0.25}{1.25s + 1} = G(s)$$

$\tilde{U}(s) \rightarrow$ **Transfer Function, G(s)** $\rightarrow \tilde{Y}(s)$

- **How to find transfer function**
    1. **Find the equilibrium point**
    2. **If the system is nonlinear, then linearize around equil. point**
    3. **Introduce deviation variables**
    4. **Take Laplace transform and solve for output**
    5. **Do the Inverse Laplace transform and recover the original variables from deviation variables**
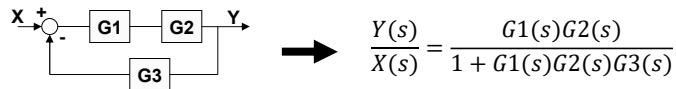
TRANSFER FUNCTION (2)

- **Benefits**
  - **Once TF is known, the output response to various given inputs can be obtained easily.**

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

  - **Interconnected system can be analyzed easily.**
    - **By block diagram algebra**

    $$\frac{Y(s)}{X(s)} = \frac{G1(s)G2(s)}{1 + G1(s)G2(s)G3(s)}$$

  - **Easy to analyze the qualitative behavior of a process, such as stability, speed of response, oscillation, etc.**
    - **By inspecting "Poles" and "Zeros"**
    - **Poles: all s's satisfying $D(s)=0$**
    - **Zeros: all s's satisfying $N(s)=0$**

TRANSFER FUNCTION (3)

- **Steady-state Gain: The ratio between ultimate changes in input and output**

  $$\text{Gain}=K = \frac{\Delta\text{ouput}}{\Delta\text{input}} = \frac{(y(\infty) - y(0))}{(u(\infty) - u(0))}$$

  - **For a unit step change in input, the gain is the change in output**
  - **Gain may not be definable: for example, integrating processes and processes with sustaining oscillation in output**
  - **From the final value theorem, unit step change in input with zero initial condition gives**

    $$K = \frac{y(\infty)}{1} = \lim_{s \to 0} s\, Y(s) = \lim_{s \to 0} s\, G(s)\frac{1}{s} = \lim_{s \to 0} G(s)$$

  - **The transfer function itself is an impulse response of the system** $Y(s) = G(s)U(s) = G(s)\mathcal{L}\{\delta(t)\} = G(s)$
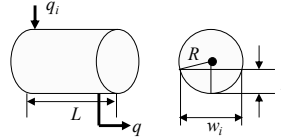
EXAMPLE

- **Horizontal cylindrical storage tank (Ex4.7)**

$$\frac{dm}{dt} = \rho \frac{dV}{dt} = \rho q_i - \rho q$$

$$V(h) = \int_0^h L w_i(\tilde{h}) d\tilde{h} \Rightarrow \frac{dV}{dt} = L w_i(h) \frac{dh}{dt}$$

$$w_i(h)/2 = \sqrt{R^2 - (R-h)^2} = \sqrt{(2R-h)h}$$

$$w_i L \frac{dh}{dt} = q_i - q \Rightarrow \frac{dh}{dt} = \frac{1}{2L\sqrt{(D-h)h}}(q_i - q) \quad \text{(Nonlinear ODE)}$$

  – **Equilibrium point:** $(\bar{q}_i, \bar{q}, \bar{h})$ $0 = (\bar{q}_i - \bar{q})/(2L\sqrt{(D-\bar{h})\bar{h}})$
    (if $\bar{q}_i = \bar{q}$ **,** $\bar{h}$ **can be any value in** $0 \le \bar{h} \le D$ **.)**
  – **Linearization:**

$$\frac{dh}{dt} = f(h, q_i, q) = \left.\frac{\partial f}{\partial h}\right|_{(\bar{h}, \bar{q}_i, \bar{q})}(h - \bar{h}) + \left.\frac{\partial f}{\partial q_i}\right|_{(\bar{h}, \bar{q}_i, \bar{q})}(q_i - \bar{q}_i) + \left.\frac{\partial f}{\partial q}\right|_{(\bar{h}, \bar{q}_i, \bar{q})}(q - \bar{q})$$

$$\left.\frac{\partial f}{\partial h}\right|_{(\bar{h}, \bar{q}_i, \bar{q})} = (\bar{q}_i - \bar{q})\frac{\partial}{\partial h}\frac{-1}{2L\sqrt{(D-h)h}} = 0 \quad (\because \bar{q}_i = \bar{q})$$

Let this term be k

$$\left.\frac{\partial f}{\partial q}\right|_{(\bar{h}, \bar{q}_i, \bar{q})} = \frac{-1}{2L\sqrt{(D-\bar{h})\bar{h}}}, \qquad \left.\frac{\partial f}{\partial q_i}\right|_{(\bar{h}, \bar{q}_i, \bar{q})} = \boxed{\frac{1}{2L\sqrt{(D-\bar{h})\bar{h}}}}$$

$$s\tilde{H}(s) = k\tilde{Q}_i(s) - k\tilde{Q}(s)$$

- **Transfer function between** $\boxed{\tilde{H}(s) \text{ and } \tilde{Q}(s): \ -\dfrac{k}{s}}$ **(integrating)**
- **Transfer function between** $\boxed{\tilde{H}(s) \text{ and } \tilde{Q}_i(s): \ \dfrac{k}{s}}$ **(integrating)**

- **If** $\bar{h}$ **is near 0 or** D**,** k **becomes very large and** $\bar{h}$ **is around** $D/2$**,** k **becomes minimum.**
- $\Rightarrow$ **The model could be quite different depending on the operating condition used for the linearization.**
- $\Rightarrow$ **The best suitable range for the linearization in this case is around** $D/2$**. (less change in gain)**
- $\Rightarrow$ **Linearized model would be valid in very narrow range near 0.**
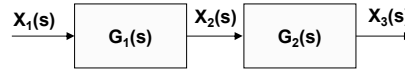
PROPERTIES OF TRANSFER FUNCTION

- **Additive property**

$$Y(s) = Y_1(s) + Y_2(s)$$
$$= G_1(s)X_1(s) + G_2(s)X_2(s)$$
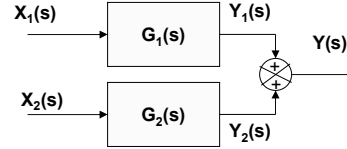
- **Multiplicative property**

$$X_3(s) = G_2(s)X_2(s)$$
$$= G_2(s)[G_1(s)X_1(s)]$$

- **Physical realizability**
  - In a transfer function, the order of numerator(m) is greater than that of denominator(n): called "physically unrealizable"
  - The order of derivative for the input is higher than that of output. (requires future input values for current output)

EXAMPLES ON TWO TANK SYSTEM

- **Two tanks in series (Ex3.7)**

Figure 3.4. Two-stage stirred-tank reactor system.

  - **No reaction**

$$V_1 \frac{dc_1}{dt} + qc_1 = qc_i$$

$$V_2 \frac{dc_2}{dt} + qc_2 = qc_1$$

  - **Initial condition:** $c_1(0) = c_2(0) = 1$ kg mol/m^3 **(Use deviation var.)**
  - **Parameters:** V_1/q=**2 min.,** V_2/q=**1.5 min.**
  - **Transfer functions**

$$\frac{\tilde{C}_1(s)}{\tilde{C}_i(s)} = \frac{1}{(V_1/q)s + 1} \qquad \frac{\tilde{C}_2(s)}{\tilde{C}_1(s)} = \frac{1}{(V_2/q)s + 1}$$

$$\frac{\tilde{C}_2(s)}{\tilde{C}_i(s)} = \frac{\tilde{C}_2(s)}{\tilde{C}_1(s)} \frac{\tilde{C}_1(s)}{\tilde{C}_i(s)} = \frac{1}{((V_2/q)s + 1)((V_1/q)s + 1)}$$
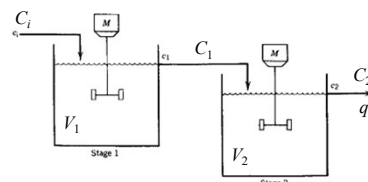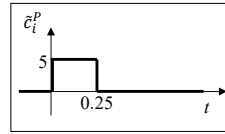
- **Pulse input**

$$\tilde{C}_i^P(s) = \frac{5}{s}(1 - e^{-0.25s})$$

- **Equivalent impulse input**

$$\tilde{C}_i^\delta(s) = \mathfrak{L}\{(5 \times 0.25)\delta(t)\} = 1.25$$

- **Pulse response vs. Impulse response**

$$\tilde{C}_1^P(s) = \frac{1}{2s+1}\tilde{C}_i^P(s) = \frac{5}{s(2s+1)}(1 - e^{-0.25s})$$

$$= \left(\frac{5}{s} - \frac{10}{2s+1}\right)(1 - e^{-0.25s})$$

$$\Rightarrow \boxed{\begin{array}{l}\tilde{c}_1^P(t) = 5(1 - e^{-t/2}) \\ \quad - 5(1 - e^{-(t-0.25)/2})\, S(t - 0.25)\end{array}}$$

$$\tilde{C}_1^\delta(s) = \frac{1}{2s+1}\tilde{C}_i^\delta(s) = \frac{1.25}{(2s+1)}$$
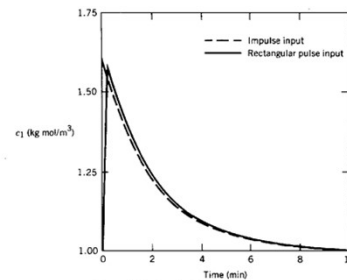
$$\Rightarrow \boxed{\tilde{c}_1^\delta = 0.625e^{-t/2}}$$

Figure 3.6. Reactor Stage 1 response.

$$\tilde{C}_2^P(s) = \frac{1}{(2s+1)(1.5s+1)}\tilde{C}_i^P(s) = \frac{5}{s(2s+1)(1.5s+1)}(1 - e^{-0.25s})$$

$$= \left(\frac{5}{s} - \frac{40}{2s+1} + \frac{22.5}{1.5s+1}\right)(1 - e^{-0.25s})$$

$$\Rightarrow \boxed{\begin{array}{l}\tilde{c}_2^P(t) = (5 - 20e^{-t/2} + 15e^{-t/1.5}) \\ \quad - (5 - 20e^{-(t-0.25)/2} + 15e^{-(t-0.25)/1.5})\, S(t - 0.25)\end{array}}$$

$$\tilde{C}_2^\delta(s) = \frac{1}{(2s+1)(1.5s+1)}\tilde{C}_i^\delta(s)$$

$$= \frac{1.25}{(2s+1)(1.5s+1)}$$

$$= \frac{5}{2s+1} - \frac{3.75}{1.5s+1}$$

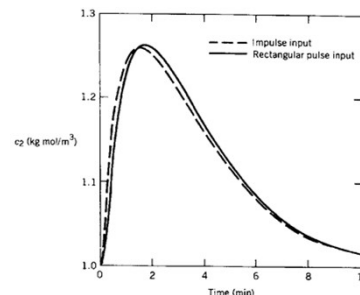$$\Rightarrow \boxed{\tilde{c}_2^\delta = 2.5e^{-t/2} - 2.5e^{-t/1.5}}$$

Figure 3.7. Reactor Stage 2 response.

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