Recap and exercises

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3 GOOD HEALTH AND WELL-BEING

SUSTAINABLE DEVELOPMENT GOAL 3:
Ensure healthy lives and promote well-being for all at all ages

https://sdgs.un.org/goals/goal3

QUESTIONS & ANSWERS
"Any time" on TELEGRAM

Friday with YAGO
@ 2pm !!

Updating the schedule...

HOMEWORK

Introduction to control systems
TI0118

Homework 1 - Project work (task 1)

Contents

Instruções e prazos

O objetivo do HW1 e da primeira tarefa do trabalho de projeto (PW) é revisar e se familiarizar com os conceitos de modelagem e representá-los na linguagem de programação de sua escolha. Você pode se referir aos slides das aulas (de L1 a L7) e os capítulos 2 e 3 de Nise para o embasamento teórico [The objective of HW1 and of the first task of the project work (PW) is to revise and familiarise with the modelling concepts and to represent them in the programming language of your choice. You might refer to the lecture slides (from L1 to L7) and Nise's chapter 2 and 3 for the theoretical background].

Guidelines: Resolver cada exercício usando cálculos teóricos e relatando as principais etapas de sua resolução. Compare, em seguida, os resultados no ambiente de programação de sua preferência. O máximo de cada questão é de 25 pontos. O resolução tem que ser enviada em um único documento e tem que deve incluir [You must solve each exercise using theoretical calculations and reporting the main steps of your resolution. Then, you compare the results on the programming environment of your choice. Each exercise pays max 25 points. The resolution must be sent in a single document and it must include]:

- Report: O relatório tem que conter (i) uma breve explicação da base teórica associada a cada exercício; (ii) os passos relevantes dos cálculos, os resultados, os gráficos (quando necessário) e, principalmente, seus comentários sobre os resultados e/ou gráficos [The report must include (i) a brief explanation of the theoretical background associated to each exercise; (ii) the relevant steps of your calculations, the results, the graphs (when required) and especially, your comments on the results and/or graphs].

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- Code listing: O código que você usou para resolver os exercícios. Independentemente da linguagem escolhida, seu código deve ser executável/funcionante. O código (e as funções relevantes, quando necessário) pode ser colado na parte final do relatório (por exemplo, como um apêndice) ou arquivado junto com o relatório em uma pasta .zip. [The code you used to solve the exercises. Regardless of your programming choice, your code must be executable/functioning. The code (and the relevant functions, when needed) can be either pasted at the end of the report (for instance as an appendix) or packaged together with the report as a zip file].

Observe que os recursos encontrados na internet devem ser referenciados adequadamente e que o uso de ferramentas de IA generativa, como o ChatGPT, apenas para copiar as respostas da tarefa não é permitido. Em vez disso, você pode usá-lo como fonte de informação, avaliando criticamente as saídas e o conteúdo que ele produz. Você deve reconhecê-lo citando-o corretamente e, por exemplo, pode considerar incluir a saída da IA generativa em um apêndice do relatório da tarefa[2] [You can base your resolution on the resources you might find on the web but you must adequately reference to them. Note that the use of generative AI tools, as such as ChatGPT, merely for copying the answers of the assignment is not permitted. Instead, you might like use it as a source of information, critically evaluating the outputs and contents that it produces. You must acknowledge it by citing it correctly and, for instance, you may like to consider including the generative AI output in an appendix of the HW report].

Team work: Os trabalhos podem ser feitos individualmente ou em dupla [The works can be done individually or in pairs].

Deadlines: Os prazos de entrega são definidos no SIGAA e podem ser diferentes para o "homework" e o projeto de trabalho [The deadlines for submissions are set in SIGAA and they can differ for the homework and project work].

- Homework : A resolução do trabalho de casa deve ser enviada através do SIGAA até o dia especificado no SIGAA. Note que os atrasos serão penalizados (<24h: 20% de penalização; <48h: 40% de penalização; etc.) [The solution of the homework must be sent through SIGAA by the deadline provided in SIGAA. Note that delays will be penalised (<24h: 20% penalty; <48h: 40% penalty; etc.)].
- Project work: O trabalho de projeto está dividido em três exercícios fornecidos juntamente com os "homework" passados durante o semestre. Podem optar por entregar a resolução dos exercícios no mesmo momento do relativo HW ou no prazo fixado para o último no final do semestre. Em ambos os casos, você deve seguir as instruções fornecidas acima. O relatório final deverá incluir a solução de cada exercício [The project work is divided into three exercises provided along with the "homework" assigned during the semester. They can choose to submit the resolution of the exercises at the same time of the relative HW or within the deadline set for the latter one at the end of the semester. In both cases, you must follow the instructions provided above. The final report must include the solution for each exercise].

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Check the updated version !!

Tuesday	Thursday
Feb. 27	Feb. 29 Course intro Background survey
Mar. 5 Systems and models	Mar. 7 Transfer functions
Mar. 12 Transfer functions	Mar. 14 Simulation of dynamic systems
Mar. 19 Feriado Estadual Dia de São José	Mar. 21 State space models
Mar. 26 Transfer function to/from State Space	Mar. 28 Recesso escolar Semana Santa
Apr. 2 1st order system	Apr. 4 2nd order system
Apr. 9 AP1	Apr. 11 Additional poles and zeros
Apr. 16 NO CLASS Block diagram representation	Apr. 18 NO CLASS Signal flow representation
Apr. 23 Stability	Apr. 25 Stability
Apr. 30 Root-Locus	May. 2 Root-Locus
May. 7 Design with RL	May. 9 Exercises Course assistants
May. 14 Exercises Course assistants	May. 16 Exercises Course assistants
May. 21 Exercises Course assistants	May. 23 Revision exercises

CHANGE of PLANS !!

EXTRA on FRIDAY MARCH 22 ? @ 2pm

EXTRA on FRIDAY APRIL 5 @ 2pm

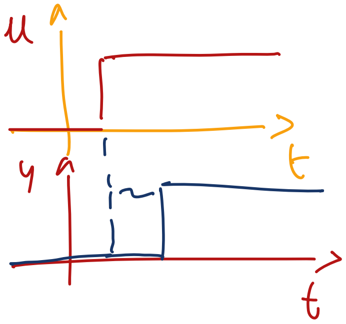
REVISION EXERCISES

to be rescheduled !!

Brief recap

So far, we did...

- Describe dynamic systems and their mathematical models as IO and SV
- Define the main properties of a mathematical model
  - Dynamic and instantaneous
  - Linear and non linear
  - Stationary and non stationary
  - Proper and improper
  - Lumped and distributed parameters
  - Time delay



$\boxed{\text{I/O representation}}$ ⇝ EXTERNAL DESCRIPTION

$$h\left(y(t), \dot{y}(t), \dots, y^{(n)}(t), u(t), \dot{u}(t), \dots, u^{(m)}(t)\right) = 0 \qquad n > m$$

$\boxed{\text{S/V representation}}$ ⇝ INTERNAL DESCRIPTION

$$\begin{cases} \dot{x}(t) = f\left(x(t), u(t), t \mid \vartheta_x\right) \\ y(t) = g\left(x(t), u(t), t \mid \vartheta_y\right) \end{cases}$$

$\theta \triangleq \vartheta$

$\sigma \triangleq \varsigma$

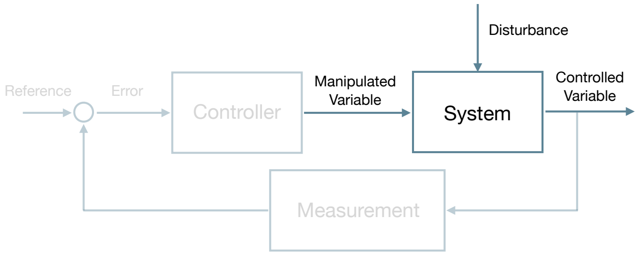
N.B. We are considering SISO systems !!

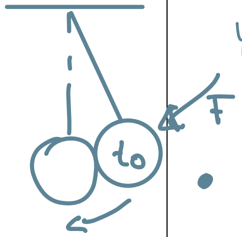
Check EXTRA NOTES on LINEARIZATION !!

Brief recap

So far, we did...

- Describe dynamic systems and their mathematical models as IO and SV
- Define the main properties of a mathematical model





FUNDAMENTAL PROBLEM of SYSTEM ANALYSIS consists of finding the behaviour of $y(t)$ as $t \geq t_0$

$$a_n \frac{d^n y(t)}{dt^n} + \dots + a_1 \frac{dy(t)}{dt} + a_0 y(t) = b_m \frac{d^m u(t)}{dt^m} + \dots + b_1 \frac{du(t)}{dt} + b_0 u(t)$$

given

- the initial conditions

$$y(t)\Big|_{t=t_0} = y_0 \qquad \frac{dy(t)}{dt}\Big|_{t=t_0} = y_0' \quad \dots \quad \frac{d^{n-1} y(t)}{dt^{n-1}} = y_0^{n-1}$$

- an input signal $u(t)$ for $t \geq t_0$

$$y(t) = y_{free}(t) + y_{forced}(t)$$

Brief recap

So far, we did...

- Review on the Laplace transform of time functions.
- Review on the inverse Laplace transform.
- Review on the partial-fraction expansion.
- Solve the differential equation using the Laplace transforms.

Modelling in the frequency domain

S-domain !!

LAPLACE TRANSFORM

→ Is an integral transform that converts a function of a real variable t (time) to a complex variable $s = \sigma + j\omega$

→ it transforms differential equations into algebraic equations and convolutions into multiplication

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

$$F(s) = \int_0^{\infty} f(t)\, e^{-st}\, dt \rightsquigarrow f(t) = \frac{1}{2\pi j} \int_{\sigma_0 - j\omega}^{\sigma_0 + j\omega} F(s)\, e^{st}\, dt$$

Brief recap

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- Review on the Laplace transform of time functions.
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Modelling in the frequency domain

S-domain !!

USEFUL PROPERTIES of LAPLACE TRANSFORM

1. LINEARITY : Given $f(t) = c_1 f_1(t) + c_2 f_2(t)$

$$F(s) = c_1 F_1(s) + c_2 F_2(s)$$

2. TIME DIFFERENTIATION $\mathcal{L}\left[\frac{d}{dt} f(t)\right] = sF(s) - f(0)$

generalising $\mathcal{L}\left[f^{(n)}(t)\right] = s^n F(s) - \sum_{i=0}^{n-1} s^{n-1-i} f^{(i)}(0)$

3. TIME - INTEGRATION : $\mathcal{L}\left[\int_0^t f(\tau)\,d\tau\right] = \frac{F(s)}{s}$

4. TIME - SHIFTING : $\mathcal{L}\left[f(t-T)\right] = e^{-Ts} F(s)$

5. SCALING $\mathcal{L}\left[e^{at} f(t)\right] = F(s-a)$

Brief recap

So far, we did...

- Review on the Laplace transform of time functions.
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Modelling in the frequency domain

S-domain !!

USEFUL PROPERTIES of LAPLACE TRANSFORM

6. TIME CONVOLUTION Given $f(t)$ and $g(t)$ such that

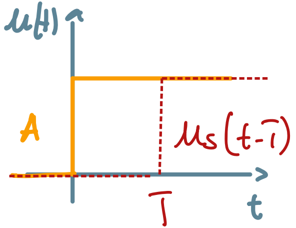
$f(t) = g(t) = 0$ for $t < 0$

$$h(t) = f(t) \cdot g(t) \rightsquigarrow H(s) = F(s)\,G(s)$$

- FINAL VALUE THEOREM. $\lim_{t \to \infty} f(t) = \lim_{s \to 0} sF(s)$

- INITIAL VALUE THEOREM $f(0^+) = \lim_{s \to \infty} sF(s)$

Brief recap

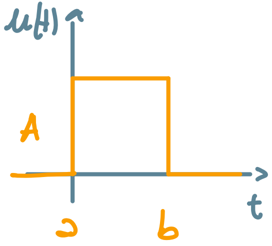


STEP FUNCTION might be realised by implementing a sudden change in the position of the actuator

$$u_s = \begin{cases} 0 & t<0 \\ A & t\geq 0 \end{cases}$$

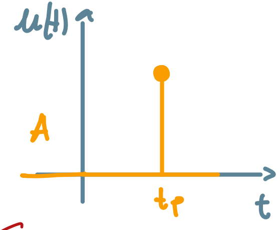
(it can be shifted)

HEAVISIDE function ⇝ $\frac{du_s}{dt} = \delta(t)$



RECTANGULAR PULSE might be realised by making an instantaneous change in the actuator position at time a and keeping it until time b

$$u_{RP} = \begin{cases} 0 & t<0 \\ h & a\leq t<b \\ 0 & t\geq b \end{cases}$$



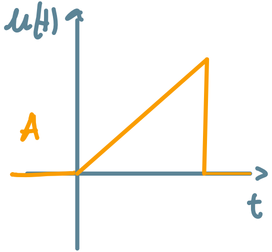
$\delta(t)$ function

$$\int_{-\infty}^{+\infty} \delta(t) = u_s(t)\Big|_{-\infty}^{+\infty} = 1$$

IMPULSE is physically impossible to implement the pulse function exactly

To obtain an impulse input, it is necessary to inject a finite amount of energy or material into the system in an infinitesimal length of time (impractical!!)

$$u_I = \begin{cases} P & t=t_P \\ 0 & \text{otherwise} \end{cases}$$



RAMP might be realised with a gradual change upward or downward for some period of time with a roughly constant slope

$$u_R = \begin{cases} 0 & t<0 \\ at & t\geq 0 \end{cases}$$

NEXT ... SINUSOIDAL INPUTS!!

Brief recap

Now, we finalise from last lecture...

- The concept of transfer function.
  - We can formulate the **system block representation** by establishing a viable definition for a function that algebraically relates a system's output to its input.
  - This function will allow separation of the input, system and output into three separate and distinct parts.
  - Transfer function also allows us to algebraically combine mathematical representations of subsystems to yield a total system representation.

$$R(s) \longrightarrow \boxed{\frac{(b_m s^m + b_{m-1}s^{m-1} + \cdots + b_0)}{(a_n s^n + a_{n-1}s^{n-1} + \cdots + a_0)}} \longrightarrow C(s)$$

RATIONAL FUNCTIONS $\rightsquigarrow$ particularly important in system analysis

$f(t)$ can be written as a linear combination of exponential ramps

$$F(s) = \frac{N(s)}{D(s)} = \frac{b_m s^m + b_{m-1}s^{m-1} + \dots + b_1 s + b_0}{a_n s^n + a_{n-1}s^{n-1} + \dots + a_1 s + a_0}$$

$\rightsquigarrow$ causal system $n \geq m$ (or $n > m$)

$D(s) \rightsquigarrow n$ roots $\rightsquigarrow p_1, \dots, p_n \to$ POLES

$N(s) \rightsquigarrow m$ roots $\rightsquigarrow z_1, \dots, z_n \to$ ZEROS

We can factorize $D(s)$ and $N(s)$ as

$N(s) = b_m (s - z_1)(s - z_2) \dots (s - z_m)$

$D(s) = a_n (s - p_1)(s - p_2) \dots (s - p_n)$

$\to F(s) = K' \frac{(s - z_1) \dots (s - z_m)}{(s - p_1) \dots (s - p_n)}$

$K' = b_m / a_n$

STATIC GAIN

MINIMAL REALIZATION

Brief recap

1. $F(s)$ has poles of UNITARY MULTIPLICITY

$$F(s) = \sum_{i=1}^{n} \frac{R_i}{s-p_i} = \frac{R_1}{s-p_1} + \frac{R_2}{s-p_2} + \dots + \frac{R_n}{s-p_n}$$

$$f(t) = \mathcal{L}^{-1}\left[F(s)\right] = \sum_{i=1}^{n} \mathcal{L}\left[\frac{R_i}{s-p_i}\right] = \sum_{i=1}^{n} R_i e^{p_i t}$$

R_i is the POLE RESIDUAL $\rightsquigarrow$ $R_i = \lim_{s \to p_i} (s-p_i)F(s)$

EXAMPLE

$$F(s) = \frac{s+8}{s^2+2s} = \frac{s+8}{s(s+2)} = \frac{R_1}{s} + \frac{R_2}{s+2}$$

$$R_1 = s \cdot F(s)\Big|_{s\to 0} = \frac{s+8}{s+2}\Big|_{s\to 0} = 4$$

$$R_2 = (s+2)F(s)\Big|_{s\to -2} = \frac{s+8}{s}\Big|_{s\to -2} = -3$$

$$F(s) = \frac{4}{s} - \frac{3}{s+2} \Longrightarrow f(t) = 4 - 3e^{-2t}$$

Brief recap

1. $F(s)$ has poles of UNITARY MULTIPLICITY

$$F(s)=\sum_{i=1}^{n}\frac{R_i}{s-p_i}=\frac{R_1}{s-p_1}+\frac{R_2}{s-p_2}+\dots+\frac{R_n}{s-p_n}$$

$$f(t)=\mathcal{L}^{-1}\left[F(s)\right]=\sum_{i=1}^{n}\mathcal{L}\left[\frac{R_i}{s-p_i}\right]=\sum_{i=1}^{n}R_i e^{p_i t}$$

R_i is the POLE RESIDUAL $\rightsquigarrow$ $R_i=\lim_{s\to p_i}(s-p_i)F(s)$

```matlab
clear; clc; close all

% Example
syms s
F=(s+8)/(s*(s+2))
pretty(ilaplace(F))
```

```python
import sympy as sym
from sympy.abc import A,a,s,t
from sympy.integrals import laplace_transform
from sympy.integrals import inverse_laplace_transform

# Example
F2 = (s+8)/(s*(s+2))
f2 = sym.inverse_laplace_transform(F2,s,t)
f2
```

python™

Brief recap

2. $F(s)$ has poles with MULTIPLICITY > 1

$$F_i(s) = \frac{R_{i,0}}{s-p_i} + \frac{R_{i,1}}{(s-p_i)^2} + \dots + \frac{R_{i,\nu_i-1}}{(s-p_i)^{\nu_i}} = \sum_{k=0}^{\nu_i-1} \frac{R_{ik}}{(s-p_i)^{k+1}}$$

$$F(s) = \sum_{i=1}^{r} F_i(s) = \sum_{i=1}^{r} \sum_{k=0}^{\nu_i-1} \frac{R_{i,k}}{(s-p_i)^{k+1}}$$

$$\mathcal{L}^{-1}\left[F_i(s)\right] = R_{ik} \frac{t^k}{k!} e^{p_i t}$$

$$\mathcal{L}^{-1}\left[F(s)\right] = \sum_{i=1}^{r} \sum_{k=0}^{\nu_i-1} R_{ik} \frac{t^k}{k!} e^{p_i t}$$

$$R_{i,\nu_i-1} = (s-p_i)^{\nu_i} F(s) \Big|_{s \to p_i}$$

$$R_{i,\nu_i-2} = \frac{d}{ds}\left[(s-p_i)^{\nu_i} F(s)\right] \Big|_{s \to p_i}$$

$$R_{i,\nu_i-3} = \frac{d^2}{ds^2}\left[(s-p_i)^{\nu_i} F(s)\right] \Big|_{s \to p_i}$$

Brief recap

2. F(s) has poles with MULTIPLICITY > 1 – EXAMPLE

$$F(s) = \frac{2}{(s+1)(s+2)^2} = \frac{R_1}{s+1} + \frac{R_2}{(s+2)^2} + \frac{R_3}{s+2}$$

$$R_1 = (s+1)\,F(s)\Big|_{s\to -1} = \frac{2}{(s+2)^2}\Big|_{s\to -1} = 2$$

$$R_2 = \frac{d}{ds}\left[(s+2)^2 F(s)\right]\Big|_{s\to -2} = \frac{d}{ds}\left[\frac{2}{s+1}\right]\Big|_{s\to -2} = 2$$

$$R_3 = (s+2)^2 F(s)\Big|_{s\to -2} = \frac{2}{s+1}\Big|_{s\to -2} = -2$$

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

$$f(t) = 2e^{-t} + 2te^{-2t} - 2e^{-2t}$$

Brief recap

3. $F(s)$ has COMPLEX CONJUGATE POLES $p, p' = \alpha \pm j\omega$

R, R' are the residuals

with $M = 2|R|$ and $\phi = \arg R$

$$\mathcal{L}^{-1}\left[\frac{R}{s+p} + \frac{R'}{s+p'}\right] = M e^{\alpha t} \cos(\omega t + \phi)$$

The POLAR representation of the residuals is

$$R = |R| e^{j\phi} \quad \text{and} \quad R' = |R| e^{-j\phi}$$

$$\mathcal{L}^{-1}\left[\frac{R}{s-p} + \frac{R'}{s-p'}\right] = R e^{pt} + R' e^{-pt} =$$

$$= |R| \left[e^{\alpha t + j(\omega t + \phi)} + e^{\alpha t - j(\omega t + \phi)} \right] =$$

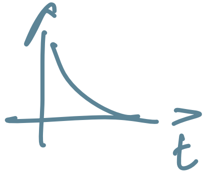
$$= |R| e^{\alpha t} \left[e^{j(\omega t + \phi)} + e^{-j(\omega t + \phi)} \right] \cdot \frac{2}{2} =$$

$$= 2|R| e^{\alpha t} \cos(\omega t + \phi) = M e^{\alpha t} \cos(\omega t + \phi)$$

EULER FORMULA

$$\cos\phi = \frac{e^{j\phi} + e^{-j\phi}}{2}$$

$$\sin\phi = \frac{e^{j\phi} - e^{-j\phi}}{2}$$



Brief recap

3. $F(s)$ has COMPLEX CONJUGATE POLES $p, p' = \alpha \pm j\omega$

$R, R' = u + jv$

With $B = 2u$ and $C = -2v$

$$\mathcal{L}^{-1}\left[\frac{R}{s-p} + \frac{R'}{s-p'}\right] = B e^{\alpha t} \cos\omega t + C e^{\alpha t} \sin\omega t$$

NOTE: Given a pair of complex conjugate poles: $p, p' = \alpha + j\omega$ and complex conjugate residuals $R, R' = u + jv$

PROOF: $\mathcal{L}^{-1}\left[\frac{R}{s-p} + \frac{R'}{s-p'}\right] = R e^{pt} + R' e^{p't} =$

$$= (u + jv) e^{\alpha t + j\omega t} + (u - jv) e^{\alpha t - j\omega t} =$$

$$= u e^{\alpha t}\left(e^{j\omega t} + e^{-j\omega t}\right) + jv e^{\alpha t}\left(e^{j\omega t} - e^{-j\omega t}\right) =$$

$$= 2u e^{\alpha t} \cos\omega t - 2jv e^{\alpha t} \sin\omega t =$$

$$= B e^{\alpha t} \cos\omega t + C e^{\alpha t} \sin\omega t$$

Brief recap

3. F(s) has complex conjugate poles

EXAMPLE

$$F(s)=\frac{20}{s(s^2+4s+5)}=\frac{20}{s(s+2+j)(s+2-j)}=$$

$$=\frac{R_1}{s}+\frac{R}{s+2+j}+\frac{R'}{s+2-j}$$

$$R_1=s.F(s)\Big|_{s\to 0}=\frac{20}{s^2+4s+5}\Big|_{s\to 0}=\frac{20}{5}=4$$

$$R'=(s+2-j)F(s)\Big|_{s\to -2+j}=\frac{20}{s(s+2+j)}\Big|_{s\to p'}=\frac{20}{(-2+j)(-2+j+2+j)}$$

$$=\frac{20(-2+j4)}{(-2-j4)(-2+j4)}=\frac{20}{20}(-2+j4)=-2+j4=u+jv$$

$$R=-2+j4$$

$$M=2|R|=2.\sqrt{2^2+4^2}=2\sqrt{20}$$

$$\phi=\arg|R|=\mathrm{arctg}\left(\frac{4}{-2}\right)\cong -2.03$$

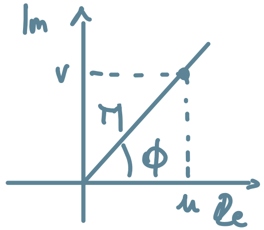
$$f(t)=4+2\sqrt{20}\,e^{-2t}\cos(t-2.03)$$

Alternatively: $B=2u=4$ $\quad C=-2v=-8$

$$f(t)=4-4e^{-2t}(\cos t+2\sin t)$$

Note: $M=\sqrt{B^2+C^2}$ $\quad \phi=\mathrm{arctg}\left(\frac{C}{B}\right)$

$B=M\cos\phi$ $\quad C=M\sin\phi$



Exercises

Exercise L4E1: Determine the Laplace transform of the following:

a. $\delta(t)$

b. $u(t)$ $\rightsquigarrow u(t) = 1$ for all $t \geq 0$

c. $\cos \omega\, t u(t)$

$\rightarrow = \frac{1}{2}\left[e^{j\omega t} + e^{-j\omega t}\right] u(t)$

a. $\mathcal{L}[\delta(t)] = \int_0^\infty \delta(t) e^{-st}\, dt = 1 \quad \forall s$

b. $\mathcal{L}[u(t)] = \int_0^\infty u(t) e^{-st}\, dt = \int_0^\infty e^{-st}\, dt =$

$= -\frac{1}{s} e^{-st} \Big|_0^\infty = \frac{1}{s}$

c. $\mathcal{L}[\cos \omega t\, u(t)] = \frac{1}{2} \mathcal{L}\left[e^{j\omega t} u(t) + e^{-j\omega t} u(t)\right]$

$= \frac{1}{2}\left[\frac{1}{s - j\omega} + \frac{1}{s + j\omega}\right] = \frac{s}{s^2 + \omega^2}$

Exercises

Exercise L4E2: Determine the inverse Laplace transform of the following:

a. $\frac{7s-6}{s^2-s-6}$ = $F(s)$

$f(t) = 4e^{-2t} + 3e^{3t}$

ToDo!!

Exercises

Exercise L4E2: Determine the inverse Laplace transform of the following:

b. $\frac{2s^2+5}{s^2+3s+2} = F(s)$

$$f(t) = 2\delta(t) + 7e^{-t} - 13e^{2t}$$

ToDo!!

Exercises

Exercise L4E2: Determine the inverse Laplace transform of the following:

c. $\dfrac{6(s+34)}{s(s^2+10s+34)} = F(s)$

$$f(t) = 6 + 10e^{-5t}(\cos(3t+2.21)) \quad \text{or}$$

$$f(t) = 6 - 6e^{-5t}\left(\cos(3t) + \frac{4}{3}\sin(3t)\right)$$

To Do!!