

# **SOLUTIONS MANUAL**

---

# **SYSTEM DYNAMICS**

---

**Fourth Edition**

---

**Katsuhiko Ogata**

---



Upper Saddle River, New Jersey 07458

Acquisitions Editor: *Laura Fischer*  
Supplement Cover Manager: *Daniel Sandin*  
Executive Managing Editor: *Vince O'Brien*  
Managing Editor: *David A. George*  
Production Editor: *Barbara A. Till*  
Supplement Editor: *Andrea Messineo*  
Manufacturing Buyer: *Ilene Kahn*



© 2004, 1998, 1992, 1978 by Pearson Education, Inc.  
Pearson Prentice Hall  
Pearson Education, Inc.  
Upper Saddle River, NJ 07458

All rights reserved. No part of this book may be reproduced in any form or by any means, without permission in writing from the publisher.

The author and publisher of this book have used their best efforts in preparing this book. These efforts include the development, research, and testing of the theories and programs to determine their effectiveness. The author and publisher make no warranty of any kind, expressed or implied, with regard to these programs or the documentation contained in this book. The author and publisher shall not be liable in any event for incidental or consequential damages in connection with, or arising out of, the furnishing, performance, or use of these programs.

Pearson Prentice Hall® is a trademark of Pearson Education, Inc.

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN 0-13-142463-7

Pearson Education Ltd., *London*  
Pearson Education Australia Pty. Ltd., *Sydney*  
Pearson Education Singapore, Pte. Ltd.  
Pearson Education North Asia Ltd., *Hong Kong*  
Pearson Education Canada, Inc., *Toronto*  
Pearson Educación de México, S.A. de C.V.  
Pearson Education—Japan, *Tokyo*  
Pearson Education Malaysia, Pte. Ltd.  
Pearson Education, Inc., *Upper Saddle River, New Jersey*

# Contents

Preface	v
Chapter 2 The Laplace Transform	1
Chapter 3 Mechanical Systems	12
Chapter 4 Transfer-Function Approach to Modeling Dynamic Systems	24
Chapter 5 State-Space Approach to Modeling Dynamic Systems	43
Chapter 6 Electrical Systems and Electromechanical Systems	89
Chapter 7 Fluid Systems and Thermal Systems	111
Chapter 8 Time-Domain Analysis of Dynamic Systems	125
Chapter 9 Frequency-Domain Analysis of Dynamic Systems	152
Chapter 10 Time-Domain Analysis and Design of Control Systems	176
Chapter 11 Frequency-Domain Analysis and Design of Control Systems	198



## **Preface**

This Solutions Manual presents solutions to all unsolved B-problems. For some problems, solutions include more materials than are required in problem statements to aid the user of the book.

The text may be used in a few different ways depending on the course objective and the time allocated to the course.

Sample course coverages are listed below.

If this book is used as a text for a quarter-length course (with approximately 30 lecture hours and 18 recitation hours), Chapters 1 through 7 may be covered.

If the book is used as a text for a semester-length course (with approximately 40 lecture hours and 26 recitation hours), then the first nine chapters may be covered or, alternatively, the first seven chapters plus Chapters 10 and 11 may be covered.

If the course devotes 50 to 60 hours to lectures, then the entire book may be covered in a semester.

The instructor will always have an option to omit certain subjects depending on the course objective.

*Katsuhiko Ogata*



# Solutions to B Problems

## CHAPTER 2

B-2-1.  $f(t) = 0 \quad t < 0$   
 $= t e^{-2t} \quad t \geq 0.$

Note that

$$\mathcal{L}[t] = \frac{1}{s^2}$$

Referring to Equation (2-2), we obtain

$$F(s) = \mathcal{L}[f(t)] = \mathcal{L}[t e^{-2t}] = \frac{1}{(s + 2)^2}$$

---

B-2-2.

(a)  $f_1(t) = 0 \quad t < 0$   
 $= 3 \sin(5t + 45^\circ) \quad t \geq 0$

Note that

$$\begin{aligned} 3 \sin(5t + 45^\circ) &= 3 \sin 5t \cos 45^\circ + 3 \cos 5t \sin 45^\circ \\ &= \frac{3}{\sqrt{2}} \sin 5t + \frac{3}{\sqrt{2}} \cos 5t \end{aligned}$$

So we have

$$\begin{aligned} F_1(s) &= \mathcal{L}[f_1(t)] = \frac{3}{\sqrt{2}} \frac{5}{s^2 + 5^2} + \frac{3}{\sqrt{2}} \frac{s}{s^2 + 5^2} \\ &= \frac{3}{\sqrt{2}} \frac{s + 5}{s^2 + 25} \end{aligned}$$

(b)  $f_2(t) = 0 \quad t < 0$   
 $= 0.03(1 - \cos 2t) \quad t \geq 0.$

$$F_2(s) = \mathcal{L}[f_2(t)] = 0.03 \frac{1}{s} - 0.03 \frac{s}{s^2 + 2^2} = \frac{0.12}{s(s^2 + 4)}$$

---

B-2-3.

$$f(t) = 0 \quad t < 0$$
$$= t^2 e^{-at} \quad t \geq 0$$

Note that

$$\mathcal{L}[t^2] = \frac{2}{s^3}$$

Referring to Equation (2-2), we obtain

$$F(s) = \mathcal{L}[f(t)] = \mathcal{L}[t^2 e^{-at}] = \frac{2}{(s+a)^3}$$

---

B-2-4.

$$f(t) = 0 \quad t < 0$$
$$= \cos 2\omega t \cos 3\omega t \quad t \geq 0$$

Noting that

$$\cos 2\omega t \cos 3\omega t = \frac{1}{2}(\cos 5\omega t + \cos \omega t)$$

we have

$$F(s) = \mathcal{L}[f(t)] = \mathcal{L}\left[\frac{1}{2}(\cos 5\omega t + \cos \omega t)\right]$$
$$= \frac{1}{2} \left( \frac{s}{s^2 + 25\omega^2} + \frac{s}{s^2 + \omega^2} \right) = \frac{(s^2 + 13\omega^2)s}{(s^2 + 25\omega^2)(s^2 + \omega^2)}$$

---

B-2-5. The function  $f(t)$  can be written as

$$f(t) = (t - a) 1(t - a)$$

The Laplace transform of  $f(t)$  is

$$F(s) = \mathcal{L}[f(t)] = \mathcal{L}[(t - a) 1(t - a)] = \frac{e^{-as}}{s^2}$$

---

B-2-6.

$$f(t) = c 1(t - a) - c 1(t - b)$$

The Laplace transform of  $f(t)$  is

$$F(s) = c \frac{e^{-as}}{s} - c \frac{e^{-bs}}{s} = \frac{c}{s} (e^{-as} - e^{-bs})$$

---



B-2-7. The function  $f(t)$  can be written as

$$f(t) = \frac{10}{a^2} - \frac{12.5}{a^2} 1\left(t - \frac{a}{5}\right) + \frac{2.5}{a^2} 1(t - a)$$

So the Laplace transform of  $f(t)$  becomes

$$\begin{aligned} F(s) &= \mathcal{L}[f(t)] = \frac{10}{a^2} \frac{1}{s} - \frac{12.5}{a^2} \frac{1}{s} e^{-(a/5)s} + \frac{2.5}{a^2} \frac{1}{s} e^{-as} \\ &= \frac{1}{a^2 s} (10 - 12.5 e^{-(a/5)s} + 2.5 e^{-as}) \end{aligned}$$

As  $a$  approaches zero, the limiting value of  $F(s)$  becomes as follows:

$$\begin{aligned} \lim_{a \rightarrow 0} F(s) &= \lim_{a \rightarrow 0} \frac{10 - 12.5 e^{-(a/5)s} + 2.5 e^{-as}}{a^2 s} \\ &= \lim_{a \rightarrow 0} \frac{\frac{d}{da} (10 - 12.5 e^{-(a/5)s} + 2.5 e^{-as})}{\frac{d}{da} a^2 s} \\ &= \lim_{a \rightarrow 0} \frac{2.5 s e^{-(a/5)s} - 2.5 s e^{-as}}{2as} \\ &= \lim_{a \rightarrow 0} \frac{\frac{d}{da} (2.5 e^{-(a/5)s} - 2.5 e^{-as})}{\frac{d}{da} 2a} \\ &= \lim_{a \rightarrow 0} \frac{-0.5 s e^{-(a/5)s} + 2.5 s e^{-as}}{2} \\ &= \frac{-0.5 s + 2.5 s}{2} = \frac{2s}{2} = s \end{aligned}$$


---

B-2-8. The function  $f(t)$  can be written as

$$f(t) = \frac{24}{a^3} t - \frac{24}{a^2} 1\left(t - \frac{a}{2}\right) - \frac{24}{a^3} (t - a) 1(t - a)$$

So the Laplace transform of  $f(t)$  becomes

$$\begin{aligned} F(s) &= \frac{24}{a^3} \frac{1}{s^2} - \frac{24}{a^2} \frac{1}{s} e^{-\frac{1}{2}as} - \frac{24}{a^3} \frac{e^{-as}}{s^2} \\ &= \frac{24}{a^3} \left( \frac{1}{s^2} - \frac{a}{s} e^{-\frac{1}{2}as} - \frac{e^{-as}}{s^2} \right) \end{aligned}$$

The limiting value of  $F(s)$  as  $a$  approaches zero is

$$\begin{aligned}
 \lim_{a \rightarrow 0} F(s) &= \lim_{a \rightarrow 0} \frac{24(1 - as e^{-\frac{1}{2}as} - e^{-as})}{a^3 s^2} \\
 &= \lim_{a \rightarrow 0} \frac{\frac{d}{da} 24(1 - as e^{-\frac{1}{2}as} - e^{-as})}{\frac{d}{da} a^3 s^2} \\
 &= \lim_{a \rightarrow 0} \frac{24(-s e^{-\frac{1}{2}as} + \frac{as^2}{2} e^{-\frac{1}{2}as} + s e^{-as})}{3a^2 s^2} \\
 &= \lim_{a \rightarrow 0} \frac{\frac{d}{da} 8(-e^{-\frac{1}{2}as} + \frac{as}{2} e^{-\frac{1}{2}as} + e^{-as})}{\frac{d}{da} a^2 s} \\
 &= \lim_{a \rightarrow 0} \frac{8 \left[ \frac{s}{2} e^{-\frac{1}{2}as} + \frac{s}{2} e^{-\frac{1}{2}as} + \frac{as}{2} \left( \frac{-s}{2} \right) e^{-\frac{1}{2}as} - s e^{-as} \right]}{2as} \\
 &= \lim_{a \rightarrow 0} \frac{\frac{d}{da} (4 e^{-\frac{1}{2}as} - as e^{-\frac{1}{2}as} - 4 e^{-as})}{\frac{d}{da} a} \\
 &= \lim_{a \rightarrow 0} \frac{-2s e^{-\frac{1}{2}as} - s e^{-\frac{1}{2}as} + as \frac{s}{2} e^{-\frac{1}{2}as} + 4s e^{-as}}{1} \\
 &= -2s - s + 4s = s
 \end{aligned}$$

B-2-9.

$$\begin{aligned}
 f(\infty) &= \lim_{t \rightarrow \infty} f(t) = \lim_{s \rightarrow 0} sF(s) \\
 &= \lim_{s \rightarrow 0} \frac{s 5(s+2)}{s(s+1)} = \frac{5 \times 2}{1} = 10
 \end{aligned}$$

B-2-10.

$$f(0+) = \lim_{t \rightarrow 0+} f(t) = \lim_{s \rightarrow \infty} \frac{s 2(s+2)}{s(s+1)(s+3)} = 0$$

B-2-11. Define

$$y = \dot{x}$$

Then

$$y(0+) = \dot{x}(0+)$$

The initial value of  $y$  can be obtained by use of the initial value theorem as follows:

$$y(0+) = \lim_{s \rightarrow \infty} sY(s)$$

Since

$$Y(s) = \mathcal{L}_+[y(t)] = \mathcal{L}_+[\dot{x}(t)] = sX(s) - x(0+)$$

we obtain

$$\begin{aligned} y(0+) &= \lim_{s \rightarrow \infty} sY(s) = \lim_{s \rightarrow \infty} s[sX(s) - x(0+)] \\ &= \lim_{s \rightarrow \infty} [s^2X(s) - sx(0+)] \end{aligned}$$

---

B-2-12. Note that

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

$$\mathcal{L} \left[ \frac{d^2}{dt^2} f(t) \right] = s^2F(s) - sf(0) - \dot{f}(0)$$

Define

$$g(t) = \frac{d^2}{dt^2} f(t)$$

Then

$$\begin{aligned} \mathcal{L} \left[ \frac{d^3}{dt^3} f(t) \right] &= \mathcal{L} \left[ \frac{d}{dt} g(t) \right] = sG(s) - g(0) \\ &= s[s^2F(s) - sf(0) - \dot{f}(0)] - \ddot{f}(0) \\ &= s^3F(s) - s^2f(0) - s\dot{f}(0) - \ddot{f}(0) \end{aligned}$$

---

B-2-13.

(a) 
$$F_1(s) = \frac{s+5}{(s+1)(s+3)} = \frac{a_1}{s+1} + \frac{a_2}{s+3}$$

where

$$a_1 = \left. \frac{s+5}{s+3} \right|_{s=-1} = \frac{4}{2} = 2$$

$$a_2 = \left. \frac{s+5}{s+1} \right|_{s=-3} = \frac{2}{-2} = -1$$

$F_1(s)$  can thus be written as

$$F_1(s) = \frac{2}{s+1} - \frac{1}{s+3}$$

and the inverse Laplace transform of  $F_1(s)$  is

$$f_1(t) = 2e^{-t} - e^{-3t}$$

(b)

$$F_2(s) = \frac{3(s+4)}{s(s+1)(s+2)} = \frac{a_1}{s} + \frac{a_2}{s+1} + \frac{a_3}{s+2}$$

where

$$a_1 = \left. \frac{3(s+4)}{(s+1)(s+2)} \right|_{s=0} = \frac{3 \times 4}{2} = 6$$

$$a_2 = \left. \frac{3(s+4)}{s(s+2)} \right|_{s=-1} = \frac{3 \times 3}{(-1) \times 1} = -9$$

$$a_3 = \left. \frac{3(s+4)}{s(s+1)} \right|_{s=-2} = \frac{3 \times 2}{(-2)(-1)} = 3$$

$F_2(s)$  can thus be written as

$$F_2(s) = \frac{6}{s} - \frac{9}{s+1} + \frac{3}{s+2}$$

and the inverse Laplace transform of  $F_2(s)$  is

$$f_2(t) = 6 - 9e^{-t} + 3e^{-2t}$$

---

B-2-14.

(a) 
$$F_1(s) = \frac{6s+3}{s^2} = \frac{6}{s} + \frac{3}{s^2}$$

The inverse Laplace transform of  $F_1(s)$  is

$$f_1(t) = 6 + 3t$$

(b)

$$F_2(s) = \frac{5s + 2}{(s + 1)(s + 2)^2} = \frac{a}{s + 1} + \frac{b_2}{(s + 2)^2} + \frac{b_1}{s + 2}$$

where

$$a = \frac{5s + 2}{(s + 2)^2} \Big|_{s = -1} = \frac{-5 + 2}{1^2} = -3$$

$$b_2 = \frac{5s + 2}{s + 1} \Big|_{s = -2} = \frac{-10 + 2}{-2 + 1} = 8$$

$$b_1 = \frac{d}{ds} \left( \frac{5s + 2}{s + 1} \right) \Big|_{s = -2} = \frac{5(s + 1) - (5s + 2)}{(s + 1)^2} \Big|_{s = -2}$$
$$= \frac{5(-1) - (-10 + 2)}{1^2} = 3$$

$F_2(s)$  can thus be written as

$$F_2(s) = \frac{-3}{s + 1} + \frac{8}{(s + 2)^2} + \frac{3}{s + 2}$$

and the inverse Laplace transform of  $F_2(s)$  is

$$f_2(t) = -3 e^{-t} + 8t e^{-2t} + 3 e^{-2t}$$

---

B-2-15.

$$F(s) = \frac{2s^2 + 4s + 5}{s(s + 1)} = 2 + \frac{2}{s + 1} + \frac{5}{s(s + 1)}$$
$$= 2 + \frac{2}{s + 1} + \frac{5}{s} - \frac{5}{s + 1} = 2 - \frac{3}{s + 1} + \frac{5}{s}$$

The inverse Laplace transform of  $F(s)$  is

$$f(t) = 2 \delta(t) - 3 e^{-t} + 5$$

---

B-2-16.

$$F(s) = \frac{s^2 + 2s + 4}{s^2} = 1 + \frac{2}{s} + \frac{4}{s^2}$$

The inverse Laplace transform of  $F(s)$  is

$$f(t) = \delta(t) + 2 + 4t$$

---

B-2-17.

$$\begin{aligned} F(s) &= \frac{s}{s^2 + 2s + 10} = \frac{s + 1 - 1}{(s + 1)^2 + 3^2} \\ &= \frac{s + 1}{(s + 1)^2 + 3^2} - \frac{3}{(s + 1)^2 + 3^2} - \frac{1}{3} \end{aligned}$$

Hence

$$f(t) = e^{-t} \cos 3t - \frac{1}{3} e^{-t} \sin 3t$$

---

B-2-18.

$$F(s) = \frac{s^2 + 2s + 5}{s^2(s + 1)} = \frac{a}{s^2} + \frac{b}{s} + \frac{c}{s + 1}$$

where

$$a = \left. \frac{s^2 + 2s + 5}{s + 1} \right|_{s=0} = 5$$

$$b = \left. \frac{(2s + 2)(s + 1) - (s^2 + 2s + 5)}{(s + 1)^2} \right|_{s=0} = \frac{2 - 5}{1} = -3$$

$$c = \left. \frac{s^2 + 2s + 5}{s^2} \right|_{s=-1} = \frac{1 - 2 + 5}{1} = 4$$

Hence

$$F(s) = \frac{5}{s^2} + \frac{-3}{s} + \frac{4}{s + 1}$$

The inverse Laplace transform of  $F(s)$  is

$$f(t) = 5t - 3 + 4e^{-t}$$

---

B-2-19.

$$F(s) = \frac{2s + 10}{(s + 1)^2(s + 4)} = \frac{a}{(s + 1)^2} + \frac{b}{s + 1} + \frac{c}{s + 4}$$

where

$$a = \left. \frac{2s + 10}{s + 4} \right|_{s = -1} = \frac{-2 + 10}{3} = \frac{8}{3}$$

$$b = \left. \frac{2(s + 4) - (2s + 10)}{(s + 4)^2} \right|_{s = -1} = \frac{6 - 8}{3^2} = \frac{-2}{9}$$

$$c = \left. \frac{2s + 10}{(s + 1)^2} \right|_{s = -4} = \frac{-8 + 10}{9} = \frac{2}{9}$$

Hence

$$F(s) = \frac{8}{3} \frac{1}{(s + 1)^2} - \frac{2}{9} \frac{1}{s + 1} + \frac{2}{9} \frac{1}{s + 4}$$

The inverse Laplace transform of  $F(s)$  is

$$f(t) = \frac{8}{3} te^{-t} - \frac{2}{9} e^{-t} + \frac{2}{9} e^{-4t}$$


---

B-2-20.

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

The inverse Laplace transform of  $F(s)$  is

$$f(t) = \frac{1}{\omega^2} \left( t - \frac{1}{\omega} \sin \omega t \right)$$


---

B-2-21.

$$F(s) = \frac{c}{s^2} (1 - e^{-as}) - \frac{b}{s} e^{-as} \quad a > 0$$

The inverse Laplace transform of  $F(s)$  is

$$f(t) = ct - c(t - a)1(t - a) - b 1(t - a)$$


---