System Dynamics and Control with Bond Graph Modeling

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To my family: Claudia, Nyssa, and Andrik

Preface

This text was written for those who teach/learn System Dynamics using bond graphs. It was designed from the onset to be undergraduate focused. As such the material is a synergy of bond graph concepts and a traditional System Dynamics curriculum. The intent was to present bond graphs as a more integrated tool within System Dynamics. Moreover, the intention was to develop a text that makes the bond graph methodology more accessible to undergraduate Engineering students. The text is purposefully designed to cater to a third or fourth year undergraduate Engineering student.

The prerequisites for this text include Linear Algebra, Ordinary Differential Equations, Engineering Mechanics, and Electrical Circuits. The reader may also benefit from exposure to Fluid Mechanics and Thermodynamics. The text includes ten chapters and can be divided into four parts – bond graph modeling, mathematical representations, analysis, and automatic control.

The first part, Chapters 1-3, focuses on synthesizing models of dynamic systems using the bond graph methodology. The first chapter is an introduction to model decomposition based on energy formalisms. This chapter introduces the reader to the needs and uses of System Dynamics. Further, the reader is shown how systems can be broken down into more basic components. The reader learns that energy and power are two unifying concepts that exist regardless of the energy domain. They are introduced to bonds, signals, and causality. In Chapter 2, the reader learns about basic bond graph elements and discovers how elements can be categorized based on their energy usage. Chapter 2 also explains the differences between linear and nonlinear systems. Since the text primarily targets linear systems, the chapter covers linearization. Finally, in Chapter 3 students learn how to synthesize bond graphs and derive differential equations.

Chapters 4-6 compose the second part which addresses state-space and transfer function representations of dynamic systems. Chapter 4 covers state-space representations. The readers learn how to convert the system of first-order differential equations derived using the bond graph model into a state-space representation. At this point, students are introduced to the use of MATLAB® for numerically simulating basic dynamic responses. (MATLAB is used through the second, third, and fourth parts of the text.) Using the state-space model, they simulate impulse, step, and ramp responses. Through Chapter 4, the focus is on time-domain representations. In Chapter 5, the students review Laplace Transforms in preparation for impedance methods and transfer function representations, which are introduced in Chapter 6. Chapter 6 covers some unique material on impedance bond graphs. The chapter is influenced by the unpublished work of Beaman and Paynter (Beaman and Paynter 1993). Students also learn how to simulate responses using transfer function representations derived from impedance bond graphs.

In Chapters 7-8, the text covers analysis, including time- and frequency-domain methods. Time-domain analysis is discussed in detail in Chapter 7. The chapter covers the characteristics of first- and second-order systems and explains how higher-order systems have responses that are the combinations of lower-order responses. In preparation for the introduction to classical control methods in Chapter 9, students learn about pole-zero analysis. Chapter 8 covers the frequency domain. Students discover methods used in the analysis of vibrating systems, AC circuits, and the like. They learn about concepts including phasor analysis, modal analysis, and bode plots.

In the final part, Chapters 9-10, the reader is introduced to automatic control methods that vary from traditional to more modern approaches. The focus in Chapter 9 is on classical methods of designing lead-lag and proportional-integral-derivative type compensators. The methods covered include the root locus method and bode plot analysis. Chapter 10, the final chapter, is intended to introduce the reader to more modern state-space approaches. The students learn how to assess controllability and observability using the state-space model. They discover how to design a compensator through pole placement and linear quadratic regulation. Additionally, they learn about the use and design of state observers.

Each chapter includes three types of exercises. The first are "review" problems or questions. These measure the reader's mastery or understanding of content. The second are simply "problems" like those commonly found in textbooks. These are designed so that the reader practices the concepts introduced in each chapter. They assess the reader's ability to implement the concepts to solve problems similar to examples in the chapter. The third and final type of exercises are "challenges." Challenges are semi-open-ended problems that require the student to transfer the knowledge learned in a manner more indicative of "real-world" problems. These challenges do not have one right answer; rather, the solution may vary based on the assumptions made by the student.

Though much of the text is unique material, it brings to bear concepts from Bond Graph Modeling, System Dynamics, and Automatic Controls. It has been influenced by several works including those of Paynter, Beaman, Ogata, Karnoop, Margolis, and Rosenburg (Beaman and Paynter 1993; Paynter 1961; Ogata 2002, 2004; Karnopp, Margolis, and Rosenberg 2000). This work has also been impacted by the course notes of Raul G. Longoria and Joseph Beaman from the Mechanical Engineering Department at the University of Texas at Austin. It is based primarily on my personal course notes for the System Dynamics course in the Mechanical Engineering Department at the University of Texas-Pan American where I have been teaching dynamic systems related courses for over a decade.

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Javier A. Kypuros

Author Biography

Javier A. Kypuros is a professor of mechanical engineering at the University of Texas-Pan American. He earned his PhD in mechanical engineering in 2001 at the University of Texas at Austin under the guidance of Dr. Raul Longoria, and his BSE in mechanical engineering from Princeton University in 1996. He has taught courses in the area of dynamic systems and control for over a decade, and has been awarded numerous grants from the National Science Foundation to develop and implement pedagogical innovations for engineering mechanics and system dynamics curricula.

Nomenclature

$1(t)$	unit step or Heaviside function
$[K]$	stiffness matrix
$[M]$	mass matrix
α	angular acceleration (rad/s^2) or attenuation factor
β	rotational damping constant (N-m-s/rad) or attenuation factor
δ	relative displacement (m)
Γ	hydraulic momentum (N-s/m^2)
γ	phase margin (degrees)
κ	rigidity (N-m/rad)
λ	flux linkage (V-s) and eigenvalues
$\mathbf{u}(t)$	input vector
$\mathbf{x}(t)$	state vector
$\mathbf{y}(t)$	output vector
$\mathscr{C}$	state controllability matrix
$\mathscr{O}$	observability matrix
$\mathscr{P}$	power (W)
$\mathscr{L}$	the Laplace transform
ω	angular velocity (rad/s)

ω_d	damping frequency (rad/s)
ω_n	natural frequency (rad/s)
$\overline{\mathscr{C}}$	output controllability matrix
$\bar{z}$	complex conjugate
ϕ	phase angle (rad)
τ	torque (N-m)
θ	angular displacement (rad)
$\tilde{\delta}(t)$	unit impulse or Dirac delta function
ζ	damping ratio
b	damping constant (N-s/m)
C	generalized compliance and capacitance (F)
C_f	hydraulic compliance (m^3/Pa)
D	PID step response delay time
e	effort and voltage (V)
E_m	electromotive force (V)
F	force (N)
f	flow
$f(t)$	a generic function of time
$G(s)$	transfer function
h	angular momentum (N-m-s)
I	generalized inertia
i	current (A)
I_f	kg/m^4
J	inertia (kg-m^2)

k spring stiffness (N/m)

K_a static acceleration error constant

K_{cr} critical gain for PID tuning

K_c overall compensator gain

K_D PID derivative gain

K_I PID integral gain

k_m motor constant (V-s/rad or N-m/A)

K_P PID proportional gain

K_p static position error constant

K_v static velocity error constant

L inductance (H)

m mass (kg)

M_p maximum percent overshoot

P pressure (Pa)

p generalized momentum, translational momentum (N-s), or pole

Q volumetric flow rate (m^3/s) or quality factor

q generalized displacement and charge (C)

R generalized resistance and electrical resistance (Ω)

R_f Pa-s/m^3

T_{cr} critical time for PID tuning

T_D PID derivative time constant

t_d delay time (s)

T_I PID integral time constant

T_p period of oscillation

t_p	peak time (s)
t_r	rise time (s)
t_s	settling time (s)
TR	transmissibility
V	volume (m^3)
v	velocity (m/s)
x	displacement (m)
Z	impedance
z	complex number or zero

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