Bond Graph in Modeling, Simulation and Fault Identification

Amalendu Mukherjee
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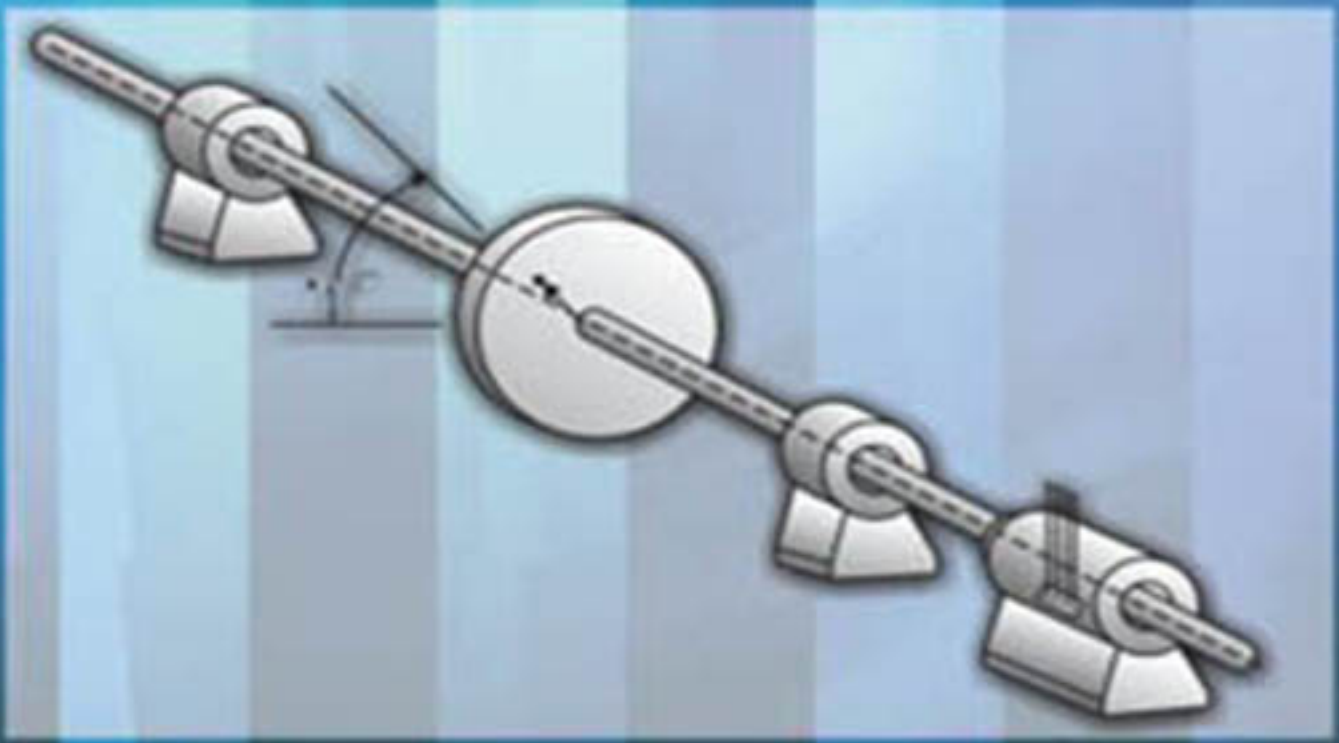
Arun Kumar Samantaray



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To our wives

Late Nita Mukherjee

Sorashi Karmakar

and

Trupti Samantaray

Preface

Bond graphs have become a part of undergraduate and postgraduate curricula at I.I.T. Kharagpur, since 1985. Bond graphs have fostered innovation and creativity in scholars, undergraduate and postgraduate students. This is manifested through a large number of doctoral dissertations and undergraduate and postgraduate projects addressing to both, theoretical aspects of bond graph theory and its wide and significant applications to the problems of industrial importance. Many industries and organization in India have included bond graphs in their research, development and design activities. Several universities and academic institutes have included bond graphs in their curricula. In the United States, Europe and Australia bond graph has very firmly developed its roots since mid seventies and now its branches are developing, bringing more and more industries and academics in its folds. The number of participants in International Conferences on Bond graph Modeling and Simulation is increasing every year.

Through sustain research in this field, in the recent years range of applications bond graphs has enhanced. These new applications are not only for system modeling but also for direct control theoretical analysis and synthesis, fault detection and isolation. A chapter in this book is devoted these aspects of bond graph modeling.

This book is an outcome of our teaching system-modeling, dynamics and control through bond graphs for the last fifteen years and its somewhat narrative style is due to a video course (of nearly 38 hours) created by Centre of Education Technology[1], I.I.T. Kharagpur, in which one of us has been the lecturer. The flavor of the narrative style is retained in this book as we realized its efficacy by observing the rapidity and depth with which the students grasped the subject.

This book has been organized into sixteen chapters. In Chapter – 1 we present the idea of Paynter and create the first impression on bond graphs followed by discussion on power variables, bond graph elements, constitutive laws and power direction. The notion of causality and laws of information exchange has been expounded in Chapter – 2 along with causality of bond graph elements, assignment of causality and a discussion on causal loop. In Chapter – 3 we present selection of system variables and a systematic procedure for the generation of system equations of state from a power directed and causalled bond graph model. Methods of creating system bond graph models and their reduction have been presented in Chapter – 4 with examples in mechanical and electrical domains. This chapter also contains

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[1] 1 Video course, "Modeling and Simulation of Dynamic Systems" by Amalendu Mukherjee. Contact Dr. Bani Bhattacharya, Centre of Education Technology, Indian Institute of Technology, Kharagpur - 721 302, India. e-mail: banib@hijli.iitkgp.ernet.in

equivalences of several transformer-gyrator-element combinations and creation of bond graph models for electrical transformer, induction and DC motors and their reduction to equivalent circuits as used by electrical engineers. In Chapter – 5 we present the principle of material objectivity and modeling of nonholonomic systems and systems in noninertial coordinates and with gyroscopic motion.

We open Chapter – 6 with a discussion on nonpotential systems and then present modeling of systems with regenerative nonpotential fields. We end this chapter with an example of modeling and simulation of a rotor with internal damping coupled to a two-phase induction motor. Chapter – 7 deals with distributed parameter systems. Modeling of Euler-Bernoulli beam, Rayleigh beam and Timoshenko beam with finite approximation is followed by creation of modal bond graph for such systems. In Chapter – 8 we present modeling of mechanisms and robotic manipulators and a bond graph based approach for computation of driving efforts. Chapter – 9 gives an overview of multi bond graph representation of systems with morphological similarities in subsystem clusters. Chapter – 10 start with the axioms of thermodynamics and establish the gas C - field with mechanical, thermal and material ports. Following this we present pseudo bond graph model for heat transfer and derived bond graph, a rational path to pseudo bond graph.

In Chapter – 11 we establish the power variables and junction structure in hydraulic circuits followed by modeling of a hydraulic servomotor. Chapter – 12 deals with the conversion of bond graph to signal flow graph and modeling of feedback control systems. Chapter – 13 brings out the power of bond graph modeling in developing control strategies from physical paradigms. In Chapter – 14 we present bond graph modeling of some basic electronic devices and circuits. Chapter – 15 is mainly devoted to applications of bond graph modeling to fault detection and isolation. This chapter also includes some significant issue of control system analysis and synthesis through bond graphs. Chapter – 16 is in three parts. Part – A presents modeling and simulation of a compressor-reservoir-muffler system. Part – B deals with modeling of a hydraulic orbit motor and in Part – C we present an application of bond graphs to non-energetic system like market economics.

The problems at the end of the chapters are divided into two groups viz. problems to be solved by students for usual practice and project type problems. Project type problems are relatively more advanced and may be used for term or short projects by students. A solution manual for the problems is also created and will be available to instructors on demand from the HighTech Consultants. Please contact to the following e-mail address or phone number: contact@htcinfo.com or +91 - 9434021009

The modified appendix describes the latest software "SYMBOLS Shakti". A CD containing a concise version of the software is provided with this book.

This book though written by three authors is an urge of an academic school, to share its joy of unified understanding of system dynamics and creativity.

A family of software created at I.I.T., Kharagpur has played very significant role in consolidating basic ideas and expanding them through large number of applications. The software SYMBOLS[2] has played the role of binding and motivating power for the school of bondgraphers at Kharagpur. Dr. Samantaray has also generated new ideas and practices which are very typical of this school. We also acknowledge the contribution of Mr. Rahul Lahiri, who as an undergraduate, initiated creation of COSMO, the predecessor of SYMBOLS, about fifteen years ago.

We acknowledge Dr. C. S. Kumar for his contributions to Chapter – 13 of this book. This chapter is based on his doctoral dissertation.

We would like to thank Dr. Ranjan Bhattacharyya, Mr. Surjya Kanta Pal and Mr. Kingshook Bhattacharyya for very lively discussions during preparation of this book.

We gratefully acknowledge Prof. A. S. R. Murty who supported us whenever the weather turned out so bad that our canopy could have blown off and foundation swept away, His sense of humour, his wisdom and his faith in us revitalized us whenever our limbs got numb in front of frustrating indifference and due to fatigue.

We are extremely grateful to Prof. M. A. Faruqui who always believed that we were devoted to a meaningful pursuit. He campaigned for our activities and provided us with all moral and material support, even going out of the way.

We express our regards and gratitude to Prof. J. U. Thoma, who, inspite of considerable discomfort, keeps visiting us, bonding us strongly with international fraternity of bondgraphers.

We thank Mr. M. R. Joshi, Director, R&D Engineers, and his colleagues who appreciated the value of this new modeling technique and helped us in conducting a national workshop on Bond graph technique, first of its kind in India. This workshop created bonds between engineers and scientists from all over India.

We acknowledge Continuing Education Programme, I.I.T. Kharagpur for partially supporting preparation of the manuscript.

We thank Mr. H. Das for sorting out software problems during preparation of the manuscript with a smile. We will ever remain grateful to our students Kumar, Arun,

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[2] See the Appendix for details on the software SYMBOLS.

Nantu, Surjya, Mohan, Kabir, Kingshook, Dilip, Rahul, Biswajit, late A. J. Sanyal and a host of others who helped us enrich our experience with bond graphs.

Finally our heartful thanks to Mr. Suvendu Banerjee who has single handedly prepared the entire manuscript, which contains more than 1000 figures and created a camera ready form of it. Mr. Banerjee ungrudgingly incorporated umpteen modifications we made and accommodated our whims and impulses and fitted them too well to give them forms of well contemplated ideas.

Kharagpur
December, 2005

Amalendu Mukherjee
Ranjit Karmakar
Arun Kumar Samantaray

Ode to the Bond Graphers

In nineteen fifty nine
Henry, the Paynter drew a line
Until that point every thing was fine
Ergs and bits then started plying
Amps, Volts, Magnet, Pressure, Price, Market
Heat, Entropy 'n Motion, with great commotion
Cooked in a potion and went unifying
No one ever since drew the final line.

By
A.M

A solution manual for the problems given in this book is also created and will be available to the instructors on demand from HighTech Consultants. A concise set of lectures on bond graph technique in video CD format (14 CDs) is also available. Please contact to the following e-mail address or phone number: contact@htcinfo.com or +91 – 9434021009.

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Notations

A	cross-sectional area
B	flux density
C	capacitance, compliance
E	energy, source of voltage
e	generalized effort
e_i	effort in i^{th} bond
F	force
f	generalized flow
f_i	flow in i^{th} bond
g	acceleration due to gravity
H	magnetic field intensity, moment of momentum
h	specific enthalpy
I	inertance
i	current
J	junction
J_i	i^{th} junction
K,k	stiffness
L	inductance
M,m	mass
$\dot{m}$	mass flow rate
n	number of turns in a coil
P	power, pressure
p	momentum
Q	displacement, charge, total heat
$\dot{Q}$	volume flow
R	resistance, resistor
S	entropy
s	specific entropy
T	temperature, kinetic energy
t	time
V	voltage
v	velocity, gas volume
X,x	coordinate direction
Y,y	coordinate direction
Z,z	coordinate direction
μ	chemical potential
ρ	density
τ	torque
ϕ	magnetic flux
Ω,ω	angular velocity
$(\dot{\cdot})$	super dot indicates time derivative

Chapter 1

Introduction

1.1 Introduction

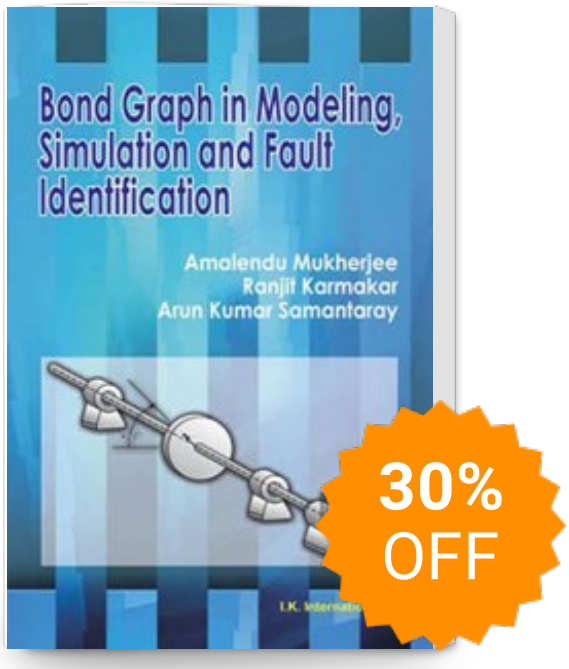
Unlike his predecessors a few generations ago, modern man has to deal with variety, diversity and is compelled to be increasingly innovative. Need for growth has become essential for survival. Though it may sound paradoxical, it is true that the only way to deal with variety and diversity and to sustain the flow of innovation is to achieve conceptual unification. Again conceptual unification is often made to shrink to techniques of creating analogues of unmanageable or unfathomable domains into fields with established empirical structures. Such an art of analogue making is not unification. Unification, in fact, should imply uniformity of symbolism, dialectics and deductive processes dissolving the partitions of experience. The requirements of a unified approach to modeling, simulation and synthesis of physical systems could be stated as follows.

(a) It should have complete but concise lexicon with validity over a large variety of diverse domains.
(b) Allow the modeler to portray the interactions within each and exchange across these domains, using aforesaid lexicon.
(c) The portraits thus created should algorithmically lead to mathematical or logical models, which may be at a higher level of abstraction (i.e., without needing any intuitive trickery). These models may then be subjected to predictive or deductive processes.

In physical systems it is energy which plays the role of common currency of exchange between various domains and sustains the business of dynamics. It is surprising that Newton's most prominent contemporary, Leibnitz [71] realized this fact. The statement of Leibnitz may appear rather strange to modernist; still the underlying idea would not be missed even at a casual glance. The statement is "*The forces are of two kinds namely dead and live. The dead force depends on position and/or on configuration and the live force is proportional to square of velocity. The sum of these two forces in the universe remains constant*".

Immediate successors of Newton and Leibnitz (John Bernoulli, Daniel Bernoulli et al) found that many problems of mechanics are formulated and solved with greater ease by this idea of Leibnitz than by the methods of Newton. If we replace the term force by energy the statement of Leibnitz is law of conservation of energy in mechanical systems.

Bond Graph In Modeling, Simulation And Fault Identification



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