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It is certified that the work contained in the thesis titled "**Modeling, Identification and IMC based PID Control of Multivariable Nonlinear Processes"** by **Durga Prasad A** is carried out under our supervision and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy and SOTA for the award of Ph.D. Degree.

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DECLARATION BY THE CANDIDATE

I, Durga Prasad A, certify that the work embodied in this thesis is the research work carried out by me under the supervision of Prof. Ram Sharan Singh (Supervisor) and Prof. Siddh Nath Upadhyay (Co-Supervisor) from December 2015 to April 2021, at the Department of Chemical Engineering & Technology, Indian Institute of Technology (Banaras Hindu University), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works are cited in my work in this thesis. I further declare that I have not wilfully copied others work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports, dissertations, thesis, etc., or available on the websites and have not included them in this thesis and have not cited as my own work.

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It is certified that the above statement made by the student is correct to the best of our knowledge.

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TO MY BELOVED MOTHER

SMT. A.V. RATNAM

WHO HAS ALWAYS VALUED EDUCATION MORE THAN ANY MATERIAL POSSESSION

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(DURGA PRASAD A)

Preface

Design of efficient control systems is vital for any process industry for maintaining the product quality, meeting the safety needs, improving the energy efficiency and reducing the environmental pollution. The conventional Proportional Integral Derivative (PID) controllers are commonly used in majority (over 95%) of the process industries due to their simple configuration and wide range of applications. Tuning of PID controller is, however, a challenging task since it involves an in-depth understanding of both dynamic and static behaviours of process. Model based controller design techniques like the Direct Synthesis (DS) method and the Internal Model Control (IMC) method have come up as superior alternatives to the conventional PID controllers since they can be implemented within the PID controller framework without any additional hardware requirements. Moreover, the DS and Internal Model Control (IMC) based PID controllers have the added advantage of possessing only one tuning parameter as compared to three in the PID controller.

A process transfer function, derived from an appropriate mathematical model is an inherent necessity for the design of model based control systems. The process modeling activity is broadly classified into two categories: (a) Theoretical modeling and (b) Process Identification. Theoretical models are based on first principles and rigorous in nature. An in-depth understanding of the physical and chemical nature of the process is the primary requirement for the development of theoretical models. Process identification, on the other hand, involves development of empirical and black (purely box data driven) models, based on extensive experimental/plant data.

From the controller design perspective, processes are categorized as Single Input Single Output (SISO) or Multiple Input Multiple Output (MIMO) processes. The Single Input Single Output (SISO) processes are simper to design since they have only one control loop involving one controlled variable (CV) and one manipulated variable (MV). The Multiple Input Multiple Output (MIMO) processes have multiple control loops and interaction among control loops is a primary factor in deciding the appropriate CV-MV pairing for each control loop.

Most chemical and biochemical processes are multivariable in nature, inherently nonlinear, possess time-varying parameters and are subjected to process uncertainties. Also chemical and biochemical reactors are known to exhibit multiple steady states and stability of the operating steady state plays an important role in the controller design methodology.

Based on the literature review and above facts, this thesis is divided into seven chapters. Chapter 1 deals with the general introduction to the process control, necessity of process control, challenges of exercising adequate control, importance of process modelling and identification in control studies, controller design strategies for Single Input Single Output (SISO) and Multiple Input Multiple Output (MIMO) processes.

Chapter 2 covers the literature review on design and tuning of Internal Model Control (IMC) based PID controller and its applications to Single Input Single Output (SISO) stable, Single Input Single Output (SISO) unstable, and Multiple Input Multiple Output (MIMO) systems. Chapter 3 provides the detailed derivations of conventional and model based controller design techniques. Chapter 4 describes the details of modeling, identification and Internal Model Control (IMC) based PID control of Two Input Two Output process (e. g. a quadruple tank setup) operated at non-minimum phase condition. Chapter 5 is devoted to an in-depth experimental and modeling study on identification and Internal Model Control (IMC) based controller design for a stable nonlinear Single Input Single Output (SISO) process (annular conical tank). Chapter 6 presents the study of theoretical modeling and Internal Model Control (IMC) based controller design for two unstable nonlinear Single Input Single Output (SISO) processes using examples of continuous bioreactor and non-adiabatic jacketed CSTR. The work is summarized and scope of future is discussed in Chapter 7. The literature cited in the thesis is referenced. The work presented in the thesis is fully documented in the form of journal publications.

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Nomenclature

s	Laplace domain
t	Time domain
$y_{sp}(s)$	Set point
$y(s)$	Process output
$\bar{y}(s)$	Process model prediction of output
$u(s)$	Controller output
$d(s)$	Load/Disturbance
$\varepsilon(s)$	Error
K_p	Steady state gain
τ_p	Time constant of process
λ	IMC (low pass filter) tuning parameter
γ	IMC (all pass filter) tuning parameter
n	Order of IMC filter
K_c	Controller gain (PID controller tuning parameter)
τ_I	Integral time (PID controller tuning parameter)
τ_D	Derivative time (PID controller tuning parameter)
θ	Dead time/Time delay
$g_c(s)$	PID controller
$g_p(s)$	Process transfer function
$g_d(s)$	Load transfer function
$g_{sp}(s)$	Closed loop transfer function (Servo problem)
$g_{load}(s)$	Closed loop transfer function (Regulator problem)
$g_f(s)$	Transfer function of final control element
$g_m(s)$	Transfer function of measuring element
$f(s)$	IMC filter transfer function
$\bar{g}_p(s)$	Process model transfer function
$\bar{g}_{p-}(s)$	Invertible part of process model transfer function
$\bar{g}_{p+}(s)$	Non-invertible part of process model transfer function
$q(s)$	IMC based open loop controller transfer function
p	Pole of transfer function
z	Zero of transfer function

F_1	Volumetric flowrate
F_{ij}	Volumetric flowrate of water flowing from Pump i to tank j.
F_{Oj}	Outlet volumetric flowrate discharging through tank j.
h_j	Height of liquid level in tank j
γ_1	Adjustable split fraction of water flowing from Pump 1 to tank 1
γ_2	Adjustable split fraction of water flowing from Pump 2 to tank 2
β_j	Nonlinear flow resistance of outlet discharge valve of tank j.
A_j	Area of tank j.
v	Linear velocity
H	Height of cylindrical tank
D	Diameter of the cylindrical tank
V_c	Volume of cone
V_a	Volume of annulus
V_T	Volume of cylindrical tank
F_i	Volumetric flowrate of inlet stream
$h_{\max}$	Height of the cone
d_1	Bottom diameter of the cone
d_2	Top diameter of the cone
β	Nonlinear flow resistance
ρ	Density of liquid
x_1	Biomass concentration
x_{1f}	Biomass concentration in feed
x_2	Substrate concentration
x_{2f}	Substrate concentration in feed
r_1	Rate of cell generation
$\mu(x_2)$	Specific growth rate coefficient
r_2	Rate of substrate consumption
Y	Yield
V	Volume
D	Dilution rate
k_0	Rate constant
ΔH	Heat of reaction
ΔE	Activation energy

C_p	Specific heat
U	Overall heat transfer coefficient
A_H	Heat transfer area
T_J	Jacket temperature
T_0	Reactor inlet temperature
T	Reactor outlet temperature
C_A	Concentration of component A

Vectors and Matrices

A	Matrix of partial derivatives with respect to state variables
B	Matrix of partial derivatives with respect to input variables
C	Matrix of constant coefficients in measurement equation
D	Matrix of constant coefficients in measurement equation
G	Matrix of multivariable transfer functions
u	Vector of input variables in deviation form
x	Vector of state variables in deviation form
$\dot{\mathbf{x}}$	Vector of time derivatives of state variables in deviation form
y	Vector of measured outputs in deviation form

Acronyms

ANN	Artificial Neural network
BC	Boundary Condition
BVP	Boundary Value Problem
CSTR	Continuous Stirred Tank reactor
CV	Controlled Variable
DS	Direct Synthesis
DV	Disturbance Variable
FOPDT	First Order Plus Dead Time
IAE	Integral of Absolute Error
IMC	Internal Model Control
IPDT	Integrator Plus Dead Time
ISE	Integral of Square of Error
ITAE	Integral of Time Absolute Error
IVP	Initial Value Problem
LHP	Left Half Plane
LPH	Litres Per Hour

MIMO	Multiple Input Multiple Output
MV	Manipulated Variable
ODE	Ordinary Differential Equation
OLETF	Open Loop Equivalent Transfer Function
OP	Output
PDE	Partial Differential Equation
PFR	Plug Flow Reactor
PID	Proportional Integral Derivative
PV	Process Variable
QPI	Quantitative Performance Index
QTP	Quadruple Tank Process
RGA	Relative Gain Array
RHP	Right Half Plane
SI	Substrate Inhibition
SISO	Single Input Single output
SOPDT	Second Order Plus Dead Time
SS	Steady State
SSE	Sum of Squares of Error
TF	Transfer function
TITO	Two Input Two Output
TV	Total Variation
VFD	Variable Frequency Drives