

MARQUES™
A V I A T I O N

Automatic Control Systems



Yuri Sokolov (Editor)

Contributing Authors
Victor Illushko
Emaid A. Abdul-Retha
Sönke Dierks
Pascual Marqués

Automatic Control Systems

Edited by

Dr. Yuri Sokolov

Contributing Authors:

Dr. Victor Iliushko, Dr. Emaid A. Abdul-Retha,

Mr. Sönke Dierks, Dr. Pascual Marqués.

Published by *Marques Aviation Ltd*
Southport, United Kingdom

MARQUES™
A V I A T I O N

Marketing Director: Elena Spiridon

ISBN 978-1-907980-10-7

Copyright © 2016 *Marques Aviation Ltd*

Copyright policy

This book remains intellectual property of *Marques Aviation Ltd*. All rights reserved. No part of this manual may be reproduced or transmitted in any form, electronically or photocopying, without permission from the copyright owner in writing, except for brief quotations embodied in critical articles and reviews. Permissions may be sought directly from *Marques Aviation Ltd* by email at admin@marquesaviation.com or via our website.

Disclaimer

The authors have exerted every effort to ensure accuracy of the information presented. Nothing in this book supersedes any procedures specified in any operational document issued by the Civil Aviation Authority or aircraft operators. The information presented is intended for training and scholarly research.

Library of Congress / British Library cataloguing-in-publication data

A catalogue record of this book is available from the British Library.

Published by *Marques Aviation Ltd*

5, Grosvenor Road, Southport, PR8 2HT, United Kingdom

Tel: 07721 784411

sales@marquesaviation.com

www.marquesaviation.com

Automatic Control Systems

Abstract

This book presents general problems of Automatic Control Theory as a base of aircraft control systems research and design. It consists of two parts: Continuous Control Systems and Digital Control Systems.

Problems of mathematical modeling, stability, accuracy, synthesis, etc. both for continuous and digital control systems are included. For this purpose the time- and frequency-domain approaches are utilized. Some design and compensation methods of the dynamic systems are presented. In spite of the wide known issues related to these problems there are few complete works concerned with computer application for analyses and design of the control systems, for example, [1, 2].

The peculiarity of this book is that it contains not only theoretical material but also an abundant number of examples and solutions. For this purpose the high-performance and complex program MATLAB is applied in the majority of sections of the book. A specific feature of the book is that the technology of computer application is considered in each illustration in detail. Thus, the principle “do as I do” is used. Owing to this approach one can solve similar control problems easily.

The book is of value for students and researchers in any field of engineering where the dynamic systems are studied.

Affiliations

Dr. Yuri Sokolov - National Aerospace University (KHAI) Ukraine.

Dr. Victor Iliushko - National Aerospace University (KHAI) Ukraine.

Dr. Emaid A. Abdul-Retha – Marques Aviation Ltd, Jordan.

Mr. Sönke Dierks – Marques Aviation Ltd, Germany.

Dr. Pascual Marqués - Marques Aviation Ltd, United Kingdom.

Contents

Preface.....	7
--------------	---

Part 1. Continuous Control Systems

1.	General concepts of automatic control theory.....	8
1.1.	A feedback control system and general design problem.....	8
1.2.	Example of the control system.....	10
1.3.	History of automatic control development.....	12
2.	Fundamentals of the control systems theory.....	14
2.1.	Fundamental principles of control.....	14
2.2.	Principal control laws.....	16
3.	Functional elements of control systems. Classification and general problems.....	20
3.1.	Functional elements of control systems.....	20
3.2.	Control systems classification.....	21
3.3.	General problems of automatic control theory.....	22
4.	Steady-state characteristics of the elements and continuous control systems.....	23
4.1.	Development of mathematical models of the systems.....	23
4.2.	Steady-state characteristics of the systems.....	24
4.3.	Linear approximation.....	24
5.	Dynamics of continuous control systems.....	27
5.1.	Ordinary differential equations.....	27
5.2.	Operational form of the differential equations.....	28
5.3.	State-vector differential equations.....	29
6.	Laplace transformation and transfer function of a system.....	34
6.1.	Laplace transformation.....	34
6.2.	Transfer function of a system.....	36
7.	Time-domain characteristics of the control systems.....	40
7.1.	The standard input signals.....	40
7.2.	Transient response and impulse response of a dynamic system.....	42
8.	Frequency domain characteristics of the control systems.....	47
8.1.	Frequency response method.....	47
8.2.	The Fourier transform.....	47
8.3.	Frequency characteristics of the systems and polar plots.....	48
9.	Bode diagram.....	52
9.1.	Logarithmic plots.....	52
9.2.	Logarithmic plot of a generalized transfer function.....	54
10.	Transfer function and frequency response of open-loop and closed- loop control systems.....	59
10.1.	Block diagrams.....	59
10.2.	Cascade connection of the blocks.....	59

10.3.	Parallel connection of the blocks.....	60
10.4.	Feedback Connection of the Blocks.....	61
10.5.	Transfer function of a closed-loop system with respect to reference, error and disturbance.....	62
11.	Signal-flow graph method.....	68
11.1.	Signal-flow graph models.....	68
11.2.	Mason's loop rule.....	68
12.	State variable models of control systems.....	73
12.1.	The state vector differential equation.....	73
12.2.	The solution of the state vector differential equation.....	73
12.3.	Signal-flow graph state model.....	74
12.4.	Determination of the transition matrix.....	76
13.	The stability of linear feedback control systems.....	83
13.1.	The concepts of stability.....	83
13.2.	A stability determination of continuous linear control systems by the roots of a characteristic equation.....	83
13.3.	Hurwitz stability criterion.....	85
13.4.	Routh-Hurwitz stability criterion.....	87
13.5.	The stability of systems in the time domain.....	93
14.	Stability criteria in the frequency domain.....	94
14.1.	The Nyquist stability criterion.....	94
14.2.	Relative stability and the Nyquist criteria. Margins of stability.....	96
14.3.	The logarithmic stability criterion.....	98
14.4.	The stability of control systems with time delays.....	99
15.	Performance of control systems.....	103
15.1.	Time-domain performance specifications.....	103
15.2.	Performance of a second-order system.....	103
15.3.	Effect of poles and zeros of higher order system on the performance of the second-order system.....	113
15.4.	Performance index and damping ratio.....	120
15.5.	Link between a transient response and roots location on the s-plane.....	122
15.6.	Steady-state errors of closed-loop control systems.....	123
15.7.	Integral performance indices.....	130
15.7.1.	Forms of integral performance indices.....	130
15.7.2.	Conditions of a minimum of integral performance index and determination of the desirable characteristic polynomial.....	132
15.8.	Simplification of linear systems.....	139
16.	The design and compensation of feedback control systems in frequency domain and using root locus method.....	140
16.1.	Types of compensation.....	140
16.1.1.	Characteristics of the phase-lead compensator.....	141
16.1.2.	Characteristics of the phase-lag compensator.....	145
16.2.	Compensators design in frequency domain and by means of the	

	root locus method.....	147
17.	Design of optimal control systems in the time domain (modal control).....	163
17.1.	Statement of the problem.....	163
17.2.	Optimality conditions and the fundamental equations.....	163

Part 2. Digital Control Systems

18.	Advantage of digital control systems.....	170
18.1.	Mathematical models of digital control systems, methods of the solution and main properties.....	170
18.1.1.	A block diagram and mathematical models of a digital control system.....	170
18.1.2.	Difference equations.....	171
18.1.3.	The z -transform.....	172
18.1.4.	Theorems of z -transformation.....	174
18.1.5.	Inverse z -transform.....	175
18.1.6.	A method of expansion into a power series.....	175
18.1.7.	A method of partial fractions decomposition and use of the z -transform table.....	176
18.1.8.	Methods of the solution of difference equations.....	177
18.1.9.	A recurrent method of the solution of difference equations.....	177
18.1.10.	The solution of difference equations using z -transformation.....	182
18.2.	Simulation of digital systems.....	183
18.3.	A transfer function and a characteristic equation of digital system..	185
18.4.	State variables equations of digital systems and eigenvalues of a matrix A	189
18.5.	The solution of state equations of digital systems.....	192
18.5.1.	A recurrent method of the solution.....	192
18.5.2.	The solution of state equations using z -transformation.....	193
18.6.	Link between state equations and a transfer function of a digital system.....	197
18.7.	Conversion of the continuous transfer functions to a discrete form...	199
18.8.	Controllability and an observe ability of digital systems.....	202
18.9.	Transfer function and time response of closed-loop digital control system.....	203
18.9.1.	Determination of a discrete transfer function and transient response of a closed-loop digital control system using block diagram	204
18.9.2.	Determination of a transient response of closed-loop digital system using Simulink model.....	206
18.9.3.	Determination of a transfer function using a difference equation of closed-loop digital control system.....	207

19.	The digital control systems stability.....	210
19.1.	A stability analysis on a z -plane.....	210
19.2.	Jury stability criterion.....	213
19.3.	Nyquist stability criterion and bilinear transformation.....	215
19.4.	Analysis of a digital systems stability using Bode diagram.....	222
20.	Performance of digital control systems.....	225
20.1.	Performance of the second-order digital control systems.....	225
20.2.	An accuracy of digital control systems in steady state.....	228
20.3.	Relation of a settling time and a phase stability margin.....	233
21.	Design of analogue and digital PID-controllers.....	236
21.1.	The purpose of design.....	236
21.2.	A numerical integration and differentiation.....	236
21.3.	The block diagram of the digital PID-controller.....	238
21.4.	Interdependence between gains of the integral and differential components of the PID-controller.....	248
21.5.	PID-controllers in MATLAB.....	249
	Selected terms and concepts used in the book	259
	References	265