

# FEEDBACK SYSTEMS

**Jose B. Cruz, Jr.**

Professor of Electrical Engineering  
University of Illinois, Urbana

with contributions by

Petar V. Kokotović

*University of Illinois, Urbana*

Eliezer Kreindler

*Grumman Aerospace Corporation*

William R. Perkins

*University of Illinois, Urbana*

Irwin W. Sandberg

*Bell Telephone Laboratories*

Philip E. Sarachik

*New York University*

26.3,

Bücherei

INSTITUT FÜR REGELUNGSTECHNIK

Technische Universität Darmstadt

Buch Nr. 2323

McGraw-Hill Book Company

New York St. Louis San Francisco

Düsseldorf Johannesburg

Kuala Lumpur London Mexico

Montreal New Delhi Panama

Rio de Janeiro Singapore

Sydney Toronto

# Contents

<b>Series Preface</b>	<b>ix</b>
<b>Preface</b>	<b>xi</b>
<b>1. Feedback in Systems</b>	<b>1</b>
<i>Jose B. Cruz, Jr., University of Illinois, Urbana</i>	
<b>1.1 Why Use Feedback?</b>	<b>1</b>
<b>1.2 Perspective</b>	<b>13</b>
Acknowledgment	16
References	16
<b>2. Sensitivity Analysis</b>	<b>19</b>
<i>William R. Perkins, University of Illinois, Urbana</i>	
<b>2.1 Comparison Sensitivity</b>	<b>20</b>
<b>2.2 A Sensitivity-reduction Criterion</b>	<b>26</b>

<b>2.3</b>	Trajectory Sensitivity Functions	33
<b>2.4</b>	Comparison Sensitivity for General Systems	52
<b>2.5</b>	Systems with Time-varying Parameters	60
	Acknowledgment	63
	References	64
<b>3.</b>	<b>Effects of Feedback on Signal Distortion in Nonlinear Systems</b>	<b>66</b>
	<i>Jose B. Cruz, Jr., University of Illinois, Urbana</i>	
<b>3.1</b>	Introduction	66
<b>3.2</b>	Nonlinear Distortion in a Single-input, Single-output Dynamic Feedback System	74
<b>3.3</b>	Nonlinear Distortion in Multivariable Feedback Systems	85
<b>3.4</b>	Relationship of Distortion to Sensitivity	92
<b>3.5</b>	Conclusion	97
	Acknowledgment	97
	References	98
<b>4.</b>	<b>Feedback Design of Large Linear Systems</b>	<b>99</b>
	<i>Petar V. Kokotović, University of Illinois, Urbana</i>	
<b>4.1</b>	Introduction	99
<b>4.2</b>	An Approximation Theorem	100
<b>4.3</b>	Coupling Perturbation Method	104
<b>4.4</b>	Singular Perturbation Method	116
	Acknowledgment	136
	References	136
<b>5.</b>	<b>Comparative Sensitivity of Optimal Control Systems</b>	<b>138</b>
	<i>Eliezer Kreindler, Grumman Aerospace Corporation</i>	
<b>5.1</b>	Introduction and Summary	138
<b>5.2</b>	Preliminaries and Problem Formulation	141
<b>5.3</b>	Comparative Performance Sensitivity of Optimal Systems	146
<b>5.4</b>	Comparative Trajectory Sensitivity of Optimal Systems	150
<b>5.5</b>	Comparative Trajectory Sensitivity: Class of Optimal Systems	155
<b>5.6</b>	Comparative Trajectory Sensitivity: Linear Optimal Systems	158
<b>5.7</b>	Comparative Trajectory Sensitivity: Saturating Optimal Systems	168
	Acknowledgment	176
	Appendix	176
	References	180
<b>6.</b>	<b>Near-Optimal Feedback Control</b>	<b>183</b>
	<i>Jose B. Cruz, Jr., University of Illinois, Urbana</i>	
<b>6.1</b>	Necessary Conditions for Near-optimal Control	185
<b>6.2</b>	Determination of Near-optimal Control	190

6.3	Approximation Property of a Class of Near-optimal Controls	215
6.4	Optimally Sensitive Controllers with Parameter Estimators	229
6.5	Conclusion	239
	Acknowledgment	239
	References	239
<b>7. On the Theory of Linear Multiloop Feedback Systems</b>		<b>241</b>
<i>Irwin W. Sandberg, Bell Telephone Laboratories</i>		
7.1	Introduction	241
7.2	The Basic System and the Set of Equations $\mathcal{F}$	242
7.3	Evaluation of the Transfer and Driving-point Functions for the Two-port	243
7.4	The Basic Flow Graph	244
7.5	The Determinants $\det \mathbf{F}_{\mathcal{F}}(\mathbf{X}_1)$ , $\det \tilde{\mathbf{F}}_{\mathcal{F}}(\mathbf{X}_1)$ , and $\det \tilde{\mathbf{F}}_{\mathcal{F}}(\mathbf{X}_1)$	247
7.6	Generalization of Blackman's Equation	248
7.7	The Matrices $\mathbf{FF}_0$ and $\tilde{\mathbf{FF}}_0$ and the Notion of a "Residual Set of Equations" Obtained from $\mathcal{F}$	252
7.8	Theorems Concerning $\det \mathbf{F}_{\mathcal{F},R}$ and $\det \tilde{\mathbf{F}}_{\mathcal{F},R}$	255
7.9	Some Simple Applications of the Theory	260
	Appendix A	265
	Appendix B	265
	References	268
<b>8. Applications of Functional Analysis to Nonlinear Control Systems with Unknown Plants</b>		<b>269</b>
<i>Philip E. Sarachik, New York University</i>		
8.1	Introduction	269
8.2	Mathematical Background	270
8.3	Iteration Methods	281
8.4	Application to Control Problems with Known Plants	288
8.5	Self-Optimizing Control with Unknown Plants	300
8.6	Conclusion	316
	References	316
<b>Name Index</b>		<b>319</b>
<b>Subject Index</b>		<b>323</b>