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Wodek K. Gawronski

Advanced Structural Dynamics and Active Control of Structures

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With 157 Figures

Springer

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To my friends—

Jan Kruszewski and
Hans Günther Natke

—scholars of dedication and imagination

Although this may seem a paradox,
all exact science is dominated by the idea of approximation.
—*Bertrand Russell*

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Mechanical Engineering Series

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Series Editor

The Mechanical Engineering Series features graduate texts and research monographs to address the need for information in contemporary mechanical engineering, including areas of concentration of applied mechanics, biomechanics, computational mechanics, dynamical systems and control, energetics, mechanics of materials, processing, production systems, thermal science, and tribology.

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Preface

Science is for those who learn;
poetry for those who know.
—*Joseph Roux*

This book is a continuation of my previous book, *Dynamics and Control of Structures* [44]. The expanded book includes three additional chapters and an additional appendix: Chapter 3, "Special Models"; Chapter 8, "Modal Actuators and Sensors"; and Chapter 9, "System Identification." Other chapters have been significantly revised and supplemented with new topics, including discrete-time models of structures, limited-time and -frequency grammians and reduction, almost-balanced modal models, simultaneous placement of sensors and actuators, and structural damage detection. The appendices have also been updated and expanded. Appendix A consists of thirteen new Matlab programs. Appendix B is a new addition and includes eleven Matlab programs that solve examples from each chapter. In Appendix C model data are given.

Several books on structural dynamics and control have been published. Meirovitch's textbook [108] covers methods of structural dynamics (virtual work, d'Alambert's principle, Hamilton's principle, Lagrange's and Hamilton's equations, and modal analysis of structures) and control (pole placement methods, LQG design, and modal control). Ewins's book [33] presents methods of modal testing of structures. Natke's book [111] on structural identification also contains excellent material on structural dynamics. Fuller, Elliot, and Nelson [40] cover problems of structural active control and structural acoustic control. Inman's book [79] introduces the basic concepts of vibration control, while Preumont in [120] presents modern approaches to structural control, including LQG controllers, sensors, and actuator placement, and piezoelectric materials with numerous applications in aerospace and civil engineering. The Junkins and Kim book [87] is a graduate-level textbook, while the Porter and Crossley book [119] is one of the first books on modal control. Skelton's work [125] (although on control of general linear systems) introduces methods designed specifically for the control of flexible structures. For example, the component cost approach to model or controller reduction is a tool frequently used in this field. The monograph by Joshi [83] presents developments on

dissipative and LQG controllers supported by numerous applications. Genta's book [65] includes rotor dynamics; the book by Kwon and Bang [92] is dedicated mainly to structural finite-element models, but a part of it is dedicated to structural dynamics and control. The work by Hatch [70] explains vibrations and dynamics problems in practical ways, is illustrated with numerous examples, and supplies Matlab programs to solve vibration problems. The Maia and Silva book [107] is a study on modal analysis and testing, while the Heylen, Lammens, and Sas book [71] is an up-to-date and attractive presentation of modal analysis. The De Silva book [26] is a comprehensive source on vibration analysis and testing. Clark, Saunders, and Gibbs [17] present recent developments in dynamics and control of structures; and Elliott [31] applies structural dynamics and control problems to acoustics. My book [47] deals with structural dynamics and control problems in balanced coordinates. The recent advances in structural dynamics and control can be found in [121].

This book describes comparatively new areas of structural dynamics and control that emerged from recent developments. Thus:

- State-space models and modal methods are used in structural dynamics as well as in control analysis. Typically, structural dynamics problems are solved using second-order differential equations.
- Control system methods (such as the state-space approach, controllability and observability, system norms, Markov parameters, and grammians) are applied to solve structural dynamics problems (such as sensor and actuator placement, identification, or damage detection).
- Structural methods (such as modal models and modal independence) are used to solve control problems (e.g., the design of LQG and H_∞ controllers), providing new insight into well-known control laws.
- The methods described are based on practical applications. They originated from developing, testing, and applying techniques of structural dynamics, identification, and control to antennas and radiotelescopes. More on the dynamics and control problems of the NASA Deep Space Network antennas can be found at http://tmo.jpl.nasa.gov/tmo/progress_report/.
- This book uses approximate analysis, which is helpful in two ways. First, it simplifies analysis of large structural models (e.g., obtaining Hankel singular values for a structure with thousands of degrees of freedom). Second, approximate values (as opposed to exact ones) are given in closed form, giving an opportunity to conduct a parametric study of structural properties.

This book requires introductory knowledge of structural dynamics and of linear control; thus it is addressed to the more advanced student. It can be used in graduate courses on vibration and structural dynamics, and in control system courses with application to structural control. It is also useful for engineers who deal with structural dynamics and control.

Readers who would like to contact me with comments and questions are invited to do so. My e-mail address is Wodek.K.Gawronski@jpl.nasa.gov. Electronic versions

of Matlab programs from Appendix A, examples from Appendix B, and data from Appendix C can also be obtained from this address.

I would like to acknowledge the contributions of my colleagues who have had an influence on this work: Kyong Lim, NASA Langley Research Center (sensor/actuator placement, filter design, discrete-time grammians, and H_∞ controller analysis); Hagop Panossian, Boeing North American, Inc., Rocketdyne (sensor/actuator placement of the International Space Station structure); Jer-Nan Juang, NASA Langley Research Center (model identification of the Deep Space Network antenna); Lucas Horta, NASA Langley Research Center (frequency-dependent grammians for discrete-time systems); Jerzy Sawicki, Cleveland State University (modal error estimation of nonproportional damping); Abner Bernardo, Jet Propulsion Laboratory, California Institute of Technology (antenna data collection); and Angel Martin, the antenna control system supervisor at the NASA Madrid Deep Space Communication Complex (Spain) for his interest and encouragement. I thank Mark Gatti, Scott Morgan, Daniel Rascoe, and Christopher Yung, managers at the Communications Ground Systems Section, Jet Propulsion Laboratory, for their support of the Deep Space Network antenna study, some of which is included in this book. A portion of the research described in this book was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Wodek K. Gawronski
Pasadena, California
January 2004

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Contents

List of Symbols

Each equation in the book
... would halve the sales.
—*Stephen Hawking*

General

A^T	transpose of matrix A
A^*	complex-conjugate transpose of matrix A
A^{-1}	inverse of square nonsingular matrix A
$\mathrm{tr}(A)$	trace of a matrix A, $\mathrm{tr}(A) = \sum_i a_{ii}$
$\lVert A \rVert_2$	Euclidean (Frobenius) norm of a real-valued matrix A: $\lVert A \rVert_2 = \sqrt{\sum_{i,j} a_{ij}^2} = \sqrt{\mathrm{tr}(A^T A)}$
$\mathrm{diag}(a_i)$	diagonal matrix with elements a_i along the diagonal
$\mathrm{eig}(A)$	eigenvalue of a square matrix A
$\lambda_i(A)$	ith eigenvalue of a square matrix A
$\lambda_{\max}(A)$	maximal eigenvalue of a square matrix A
$\sigma_i(A)$	ith singular value of a matrix A
$\sigma_{\max}(A)$	maximal singular value of a matrix A
I_n	identity matrix, $n \times n$
$0_{n\times m}$	zero matrix, $n \times m$

Linear Systems

(A,B,C,D)	quadruple of the system state-space representation
(A,B,C)	triple of the system state-space representation
(A_d, B_d, C_d)	discrete-time state-space representation
$(A_{lqg}, B_{lqg}, C_{lqg})$	LQG controller state-space representation
$(A_\infty, B_\infty, C_\infty)$	H_∞ controller state-space representation
(A_o, B_o, C_o)	closed-loop state-space representation
G	transfer function
G_d	discrete-time transfer function
H_1	Hankel matrix
H_2	shifted Hankel matrix
h_k	kth Markov parameter
U	input measurement matrix
Y	output measurement matrix
x	system state
x_e	system estimated state
u	system (control) input
y	system (measured) output
z	performance output
w	disturbance input
B_1	matrix of disturbance inputs
B_2	matrix of control inputs
C_1	matrix of performance outputs
C_2	matrix of measured outputs
$\|G\|_2$	continuous-time system H_2 norm
$\|G\|_\infty$	continuous-time system H_∞ norm
$\|G\|_h$	continuous-time system Hankel norm
$\|G_d\|_2$	discrete-time system H_2 norm
$\|G_d\|_\infty$	discrete-time system H_∞ norm
$\|G_d\|_h$	discrete-time system Hankel norm
$\mathcal{C}$	controllability matrix
$\mathcal{O}$	observability matrix
W_c	controllability grammian
W_o	observability grammian
γ_i	ith Hankel singular value
$\gamma_{\max}$	the largest Hankel singular value of a system
Γ	matrix of Hankel singular values
CARE	controller algebraic Riccati equation
FARE	filter (or estimator) algebraic Riccati equation
HCARE	H_∞ controller algebraic Riccati equation

HFARE	H_∞ filter (or estimator) algebraic Riccati equation
S_c	solution of CARE
S_e	solution of FARE
$S_{\infty c}$	solution of HCARE
$S_{\infty e}$	solution of HFARE
μ_i	ith LQG singular value
$\mu_{\infty i}$	ith H_∞ singular value
M	matrix of the LQG singular values, $\mathrm{M} = \mathrm{diag}(\mu_i)$
M_∞	matrix of the H_∞ singular values, $\mathrm{M}_\infty = \mathrm{diag}(\mu_{\infty i})$
ρ	parameter of the H_∞ controller
K_c	controller gain
K_e	estimator gain
ε	tracking error
t	time sequence
Δt	sampling time
N	number of states
s	number of inputs
r	number of outputs

Structures

D	damping matrix
K	stiffness matrix
M	mass matrix
D_m	modal damping matrix
K_m	modal stiffness matrix
M_m	modal mass matrix
q	structural displacement (nodal)
q_m	structural displacement (modal)
q_{ab}	structural displacement (almost-balanced)
q_i	displacement of the ith degree of freedom
q_{mi}	displacement of the ith mode
q_{abi}	displacement of the ith almost-balanced mode
ϕ_i	ith structural mode
ϕ_{abi}	almost-balanced ith structural mode
Φ	modal matrix
Φ_{ab}	almost-balanced modal matrix
ω_i	ith natural frequency
Ω	matrix of natural frequencies

ζ_i	*i*th modal damping
Z	matrix of modal damping coefficients
B_o	nodal input matrix
C_{oq}	nodal displacement output matrix
C_{ov}	nodal velocity output matrix
B_m	modal input matrix
C_{mq}	modal displacement output matrix
C_{mv}	modal velocity output matrix
C_m	modal output matrix, $C_m = C_{mq}\Omega^{-1} + C_{mv}$
b_{mi}	input matrix of the *i*th mode, *i*th row of B_m
c_{mi}	output matrix of the *i*th mode, *i*th column of C_m
$\lVert B_m \rVert_2$	modal input gain
$\lVert C_m \rVert_2$	modal output gain, $\lVert C_m \rVert_2^2 = \lVert C_{mq}\Omega^{-1} \rVert_2^2 + \lVert C_{mv} \rVert_2^2$
$\lVert b_{mi} \rVert_2$	input gain of the *i*th mode
$\lVert c_{mi} \rVert_2$	output gain of the *i*th mode
$\Delta\omega_i$	*i*th half-power frequency, $\Delta\omega_i = 2\zeta_i\omega_i$
σ_{2ij}	H_2 placement index for the *i*th actuator (sensor) and the *k*th mode
$\sigma_{\infty ij}$	H_∞ placement index for the *i*th actuator (sensor) and the *k*th mode
Σ_2	H_2 placement matrix
Σ_∞	H_∞ placement matrix
$I(k)$	membership index of the *k*th sensor
β_i	pole shift factor
n_d	number of degrees of freedom
n	number of modes
N	number of states
s	number of inputs
r	number of outputs
S	number of candidate actuator locations
R	number of candidate sensor locations