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T.C. Manjunath
M. Umapathy

Modeling, Control and Implementation of Smart Structures

A FEM-State Space Approach

Springer

B. Bandyopadhyay · T.C. Manjunath · M. Umapathy

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A FEM-State Space Approach

With 142 Figures

Springer

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"Where the mind is without fear and the head is held high;
Where knowledge is free;
Where the world has not been broken up into fragments by narrow domestic walls;
Where words come out from the depth of truth;
Where tireless striving stretches its arms towards perfection;
Where the clear stream of reason has not lost its way into the dreary desert sand of dead habit;
Where the mind is led forward by thee into ever-widening thought and action - - -
Into that heaven of freedom, my Father, let my country awake."

..... *Rabindranath Tagore*

Dedicated to our Wives

Tamisra, Uma, Sujatha

and
Children

Trisha, Nidhisha and Nikhitha, Rahul

Preface

Smart materials and smart structures, often called as the intelligent structures forms a new rapidly growing interdisciplinary technology in the modern day world embracing the fields of materials, structures, mechatronics, sensor - actuator systems, information and signal processing, electronics, mathematics, control and are basically distributed parameter systems.

A common feature in majority of the structures is the active vibration control problem, which has to be dealt with as it would lead to the degradation of the structural performance if left uncontrolled. A modest attempt is made to reduce the structural vibrations in smart cantilever beam using various control strategies and is presented in this monograph, which is entirely based on the authors work. Some of the developed control techniques are also experimentally verified.

Much of the research work done in the area of smart structures so far is mainly concentrated in the modeling and control techniques, static and dynamic analysis which make use of state feedback, output feedback principles, linear quadratic regulator, optimal control and PID based techniques, etc.,. Since most of these types of control techniques needs all the system states for feedback, which may not be available for measurement, they may suffer from the problem of real time implementation and some times need a state observer for control purposes. These drawbacks could be overcome by the use of multirate output feedback techniques (MROF).

With the increasing use of computers and discrete-time samplers in controller implementation in the recent past, discrete-time systems and computer based control have become the topics that have a lot of potential in them. An MROF based control technique can be applied to almost all the systems which are controllable and observable, while at the same time being simple enough as not to tax the computers too much.

State feedback algorithms can be converted into output feedback algorithms by the use of multirate output feedback sampling technique. Consequently, the MROF based control strategies has the advantages of both the state feedback and output feedback control philosophies. This has further opened up the field of multirate output feedback based discrete time sliding mode control of smart structures.

The authors would like to express their deep sense of gratitude to their parents and teachers who have made them capable enough to write this book.

The authors wish to place on record their hearty thanks to many of the individuals who had helped them directly or indirectly in completing this monograph. Notable among them being Prof. P. Seshu of Mechanical Engineering Department, IIT Bombay, who had helped the authors by giving constructive suggestions in the preparation of some part of this monograph. The authors would like to thank Prof. P.S.V. Nataraj of Systems and Control Engg. Dept. for his cooperation during the preparation of this monograph.

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Tadaga Channaveerappa Manjunath
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Nomenclature

List of Roman symbols:

a_1 to a_4	Constants used in the solution of the displacement function
a_c	Actuator constant
A	Area (m^2, mm^2)
A_{11}	Extensional coefficient
A_{55}	Transverse shear stiffness coefficient
A_b	Area of the beam element
$\hat{A}$	Diagonalized A matrix consisting of eigen values
A_p	Area of the beam piezoelectric element (m^2, mm^2)
A, $\mathbf{A}$	State matrix in continuous-time model of LTI system,
b	Width of the beam or piezoelectric sensor or actuator (m, cm, mm)
B	Spatial derivative of the vector of inertial forces $\mathbb{N}$
B, $\mathbf{B}$	Input matrix in continuous-time model of LTI system
B_{11}	Bending-extensional coefficient
c	Constant which is given by $\sqrt{\frac{EI}{\rho A}}$, width of the beam
C, $\mathbf{C}$	Output matrix in continuous-time model of LTI system
$\mathbf{C}_0$, $\mathbf{D}_0$	Fictitious matrices or the matrices of the lifted system
$\mathbf{C}(F, N)$	Fictitious measurement matrix
$\mathbf{C}^*$	Generalized structural modal damping matrix
d_{15}, d_{31}	Piezoelectric constants
$d(k)$, $\tilde{d}(k)$	Bounded disturbance
d_l, d_u	Known lower and upper bounds on the disturbance
dA	Elemental area (m^2, mm^2)
dx	Elemental length along the x-axis (m, mm)
D, $\mathbf{D}$	Transmission matrix in continuous-time model of LTI system
D_z	Electric displacement

D_{11}	Bending coefficient
e	Permittivity of the medium (dielectric constant)
$e(k)$	Variable resulting due to effect of disturbance on sampled output
$e_l,\ e_u$	Lower and upper bounds of $e(k)$
e_0	Mean (average value) of the function of uncertainty
e_{31}	Piezoelectric stress/charge constant
e_{15}	Piezoelectric constant
E_{11}	Actuator induced piezoelectric axial force
E_b	Young's modulus of the beam, modulus of elasticity (GPa)
E_p	Young's modulus of the piezo patch or modulus of elasticity (GPa)
E_f	Electric field (V)
$E,\ \mathbf{E}$	External load matrix which couples disturbance to the system
E	Young's modulus or modulus of elasticity (GPa)
EI	Flexural rigidity
f	Frequency (Hertz)
$\mathbf{f}_{ext}$	External force, i.e., disturbance applied to the beam (N)
$\mathbf{f}^*_{ext}$	Generalized external force vector
$\mathbf{f}_{ctrl\ i}$	Control force coefficient vector
$\mathbf{f}^*_{ctrl\ i}$	Generalized control force coefficient vector
$\mathbf{f}^{\ t}$	Total force coefficient vector
$\mathbf{f}^*_t$	Generalized total force coefficient vector
$f_i(x)$	Shape functions of the beam
$F_1,\ F_2$	Forces acting at the nodes 1 and 2 (N)
F	State feedback gain
F_{11}	Actuator induced bending moment
g_{31}	PZT stress constant (VmN^{-1})
$\mathbf{g}$	Generalized coordinates
G_c	Signal conditioning device gain
G_{55}	Actuator induced shear force
G_i	Output injection gain
$\mathbf{h}$	Constant vector which depends on actuator characteristics
h	Height of the beam + 2 piezo patches, i.e., the thickness of total structure ($m,\ mm$)
$i(t)$	Sensor current ($Amps$)
$i,\ j$	Variables, i.e., 1, 2, 3,....
I_b	Moment of inertia of the beam
I_p	Moment of inertia of the piezoelectric patch
I	Identity matrix
$I_1,\ I_2,\ I_3$	Mass inertias of the cross-section of the beam
k^*	Positive integer chosen by the designer
k	Discrete samples

K^b	Stiffness matrix of the regular beam element, i.e., local stiffness matrix
K^p	Stiffness matrix of the piezoelectric element, i.e., local stiffness matrix
K_c	Controller gain
K	Stiffness matrix of the piezoelectric beam element
$\mathbf{K}$	Assembled stiffness matrix of the beam, i.e., global stiffness matrix Periodic output feedback gain matrix
$\mathbf{K}^*$	Generalized stiffness matrix of the beam
l_p	Length of piezo patch (either sensor/actuator) (m or cm or mm)
l_b	Length of the beam element (m or cm or mm)
$\mathbf{L}$	Fast output sampling feedback gain matrix
L_b	Total length of the beam (m or cm or mm)
L_j	Matrix blocks represent the output feedback gains
m	Moment along the length of the beam
M_1, M_2	Bending moments acting at node 1 and 2
M^b	Mass of the regular beam element, i.e., local mass matrix
M_a	Resultant moment acting on the structure
M^p	Mass matrix of the piezoelectric element
M	Mass matrix of the piezoelectric beam element
$\mathbf{M}$	Assembled mass matrix of the beam, i.e., global mass matrix
$M_{\rho_b A_b}$	Mass matrix of the beam associated with the translational inertia
$M_{\rho_p A_p}$	Mass matrix of piezoelectric element associated with translational inertia
$M_{\rho_b I_b}$	Mass matrix of the beam associated with the rotary inertia
$M_{\rho_p I_p}$	Mass matrix of the piezoelectric element associated with the rotary inertia
$\mathbf{M}^*$	Generalized mass matrix of the beam
M_x	Bending moment
$\mathbf{n}_i^T$	Spatial derivative of the shape functions
N_w^T	Mode shape functions for displacement taking shear into consideration
N_θ^T	Mode shape functions for velocity taking shear into consideration

N_a^T	Mode shape functions for acceleration taking shear into consideration
N_x	Internal forces acting on the cross section of the beam, i.e., axial force
N_a	Number of actuators
N	Number of layers of the beam, Number of sub-intervals
$\mathbf{p}$	Constant vector which depends on sensor characteristics
P	Transformation matrix
P_{11}, P_{21}	$(r \times r)$ and $(n-r) \times r$ sub-matrices obtained by partitioning of P matrix
$q(x,t)$	Externally applied pressure loading at the tip of the beam
$q(t)$	Charge accumulated on the sensor surfaces
$\mathbf{q}$	Vector of displacements and slopes, i.e., nodal displacement vector Principal coordinates
$\dot{\mathbf{q}}$	Velocity vector
$\ddot{\mathbf{q}}$	Acceleration vector
q_d	Distributed force along the length of the beam
q_0	Transverse distributed loading
$Q(t)$	Total charge developed on sensor surface (Coloumbs)
Q_{xz}	Shear force
$\overline{Q}_{11}$, $\overline{Q}_{55}$	Constants of the composite beam
$r(t)$	Reference input to the beam, i.e., impulse or sinusoidal disturbance
$s(k)$	Switching function or the sliding function or the switching surface
sgn	Signum function
s^σ	Compliance of the medium
$s_d(k)$	apriori known function
S_c	Sensor constant
t_b	Thickness of the beam (m or cm or mm)
t_a	Thickness of the actuator (m or cm or mm)
t_s	Thickness of the sensor (m or cm or mm)
t	Time (sec)
$\mathbf{T}$	Modal matrix containing eigenvectors representing desired number of modes
T	Transpose, Kinetic energy
u_0	Initial control
$u_0(x)$	Axial displacement of a point on the composite beam
$\hat{u}$	Stabilizing control for the reduced order model
u	Control input applied to actuator from controller (V) Axial displacement along the x-axis (mm)

$\mathbf{u}(t)$	Input vector
U	Strain energy
v	Lateral displacement along the y-axis
$V^s(t)$	Sensor voltage (V)
$V^a(t)$	Actuator voltage (V)
$V^k(x,t)$	Applied voltage to k^{th} actuator having a thickness of $\left(z_{k+}^a - z_{k-}^a\right)$
$w_0(x)$	Lateral displacement of a point on the composite beam
$w(x,t)$	Displacement function
$w'(x,t)$	First spatial derivative of the displacement function
$w'(x,t)$	Second spatial derivative of the displacement function
w_i, θ_i	Degrees of freedom at the nodes
$\dot{w}(x,t)$	Time derivative of the displacement function
w	Transverse displacement (mm)
W	External work done
x	Distance of the local coordinate from the fixed end State variable or axis
x_0	Initial state
$\mathbf{x}(t)$	State vector in CT consisting of state variables $x_1,\ x_2, \ldots$
$\mathbf{x}(k)$	State vector in DT consisting of samples at $k\ =\ 0,1,2,3,..$
$y(t),\ y_i$	System output, i.e., sensor o/p of the CT system (volts)
y_τ	Output sampled at τ
$y(k)$	System output, i.e., sensor o/p of the DT system (Volts)
y	Axis
z_k	Distance of the k^{th} layer from the x-axis
$z_1,\ z_2$	r and $(n-r)$ dimensional state vectors corresponding to the original state variables
z	Distance from the center of the beam to the piezo patch, i.e., $\left(t_a + \frac{t_b}{2}\right)$ (mm) Axis Depth of the material point measured from beam reference plane along vertical axis (mm)
$\bar{z},\ \bar{h}$	Distance between neutral axis of the beam and the PE layer $\left(\frac{t_a+t_b}{2}\right)$ (mm)
Z_i	Vector of forces and moments

List of Greek symbols:

α	Frictional damping constant
β	Structural damping constant
δ_e	Variation (maximum deviation) of the function of the uncertainty
$\delta\Pi$	Change in energy
δ	Half the quasi sliding mode band width
δU	Variation in the strain energy
δT	Variation in the kinetic energy
δW_e	Variation in the work done due to the external forces
ϵ	Belongs to
ε	Strain
ε_{xx}, ε_{yy}, ε_{zz}	Longitudinal strains or the tensile strains in the x, y and z directions
ε_x	Mechanical normal strain
ε_z	Transverse shear strain
ϕ	Ratio of the beam bending stiffness to shear stiffness
$\phi(x)$	Bending slope
$(\Phi_\tau, \Gamma_\tau, C)$	DT system obtained by sampling CT system with sampling interval of τ sec. Tau system
(Φ, Γ, C)	DT obtained by sampling CT system with sampling interval of Δ sec. Delta system
$\tilde{\Phi}, \tilde{\Gamma}, \tilde{C}^T$	Augmented DT system
γ	Shear strain Controllability index of the system
γ_{xz}, γ_{yz}, γ_{xy}	Shear strains in the 3 directions
$\gamma(x)$	Additional shear deformation angle
$\mathbb{K}$	Shear coefficient
$\mathbb{G}$	Shear modulus or modulus of rigidity
λ	Angle between the fiber direction and the longitudinal axis of the beam Eigen values of the system
υ	Poisson's ratio Observability index of the system

$\mathbb{N}$	Vector of inertia forces
π	$\frac{22}{7}$
θ	Time dependent rotation of the beam cross section about the y-axis Angle of rotation or slope in EB beam($rads$ or $degs$)
ρ_b	Density of the beam (Kg/m^3)
ρ_p	Density of the piezoelectric patch (Kg/m^3)
ρA	Mass / unit length
$\rho(\cdot)$	Spectral radius
ρ_1, ρ_2, ρ_3	LMI norms
$\Re^n$	n-dimensional real space
$\Re^m$	m-dimensional real space
$\Re^p$	p-dimensional real space
σ_a	Stress in the actuator
σ	Stress
σ_{xz}	Shear stress
σ_x	Normal shear stress
σ_{xx}	Tensile stress
τ	Sampling interval ($secs$)
τ_{xz}	Shear stress
ω	Natural frequency ($rads/sec$)
ξ	Damping ratio

List of Acronyms/Abbreviations:

ADC	Analog to Digital Converter
AVC	Active Vibration Control
CC	Clamped Clamped
CF	Clamped Free
CL	Closed Loop
CT	Continuous Time
DAC	Digital to Analog Converter
DOF	Degree Of Freedom
DSM	Discrete Sliding Mode
DSMC	Discrete Sliding Mode Control
DT	Discrete Time
DTQSMC	Discrete Time Quasi Sliding Mode Control
DTSMC	Discrete Time Sliding Mode Control
EB	Euler-Bernoulli
ER	Electro Rheological
FE	Finite Element

FEM	Finite Element Method
FFT	Fast Fourier Transform
FOS	Fast Output Sampling
FOSSMC	Fast Output Sampling based Sliding Mode Control
HOBT	Higher Order Beam Theory
IEEE	Institute of Electrical and Electronics Engineers
IOP	Institute of Physics
ISSS	Institute of Smart Structures and Systems
LHS	Left Hand Side
LMI	Linear Matrix Inequalities
LTI	Linear Time Invariant
LTI	Linear Time Invariant
MATLAB	MATrix LABoratory
MEMS	Micro Electronic Mechanical Systems
MIMO	Multiple Input Multiple Output
MR	Magneto Rheological
MROF	Multi-Rate Output Feedback
NEMS	Nano Electronic Mechanical Systems
OL	Open Loop
PC	Personal Computer
PCI	Personal Computer Interface
PE	Piezo Electric
POF	Periodic Output Feedback
PVC	Poly Vinyl Chloride
PVDF	Poly Vinylidene Fluoride
PZT	Lead Zirconate Titanate
QSM	Quasi Sliding Mode
QSMC	Quasi Sliding Mode Control
RDFOS	Robust Decentralized Fast Output Sampling
RDPOF	Robust Decentralized Periodic Output Feedback
RHS	Right Hand Side
RTI	Real Time Interface
RTW	Real Time Workshop
SFB	State Feedback Gain
SISO	Single Input Single Output
SMA	Shape Memory Alloys
SMC	Sliding Mode Control
SPIE	Society of Photonics and Instrumentation Engineers
SS	State Space
TLC	Target Language Compiler

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