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Thomas Kletschkowski
Department of Mechanical Engineering,
Mechatronics
Helmut-Schmidt-University/University
of the Federal Armed Forces Hamburg
Holstenhofweg 85
Hamburg 22043
Germany
kletsch@hsu-hh.de

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Preface

This book focuses on a mechatronic approach to active control of interior noise. It strives to comprehend the results of a five year research period as chief engineer with the chair for mechatronics of the Helmut-Schmidt-University/University of the Federal Armed Forces Hamburg.

Although the book starts with fundamental concepts, the reader is expected to be familiar with engineering mechanics and/or engineering acoustics (including experimental techniques), system theory and numerical mathematics. The target audience therefore consists of post graduate students, professional engineers, and researchers working in mechatronics, and especially in the field of active interior noise control.

At the beginning of each new chapter, an abstract contains both a short summary and, as recommendations for further reading, a brief comment on literature. The important contributions to the subject matter are quoted throughout the text. However, the list of references is far from being complete. I therefore apologize to any colleagues not mentioned in spite of their important contributions to academic and/or applied research on active noise and vibration control.

Hamburg, Germany

Thomas Kletschkowski

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Notation

Mathematical Operations and Operators

div	Divergence operator
grad	Gradient operator
max	Maximum operator
min	Minimum operator
E	Expectation
$\mathfrak{F}$	Fourier transform
$\mathfrak{F}^{-1}$	Inverse Fourier transform
$\mathfrak{F}_d$	Fourier transform of sampled signals
$\mathfrak{F}_d^{-1}$	Inverse Fourier transform of sampled signals
$\mathfrak{F}_{DFT}$	Discrete Fourier transform
$\mathfrak{F}_{DFT}^{-1}$	Inverse Discrete Fourier transform
Im	Gives the imaginary part of a complex number
Re	Gives the real part of a complex number
$\mathfrak{T}$	Transformation
$\circ\!\!-\!\!\bullet$	Mapping from time domain to frequency domain
$\bullet\!\!-\!\!\circ$	Mapping from frequency domain to time domain
$\Box$	Wave operator
$\vec{\Box}$	Vector wave operator
$(\,)^T$	Transposition
$(\,)^H$	Hermitian or conjugate transpose (of a matrix)
$d(\,)$	Total derivative
$\partial(\,)$	Partial derivative
$\overline{(\,)}$	Arithmetic mean
$\mathrm{tr}(\,)$	Trace of a matrix
$\Vert\;\Vert_2$	Euclidean norm

Conventions for Signals and Systems

Conventions for Continuous-Time Signals and Systems

t	Time
f	Frequency

ω	Angular frequency, i.e. 2π times the actual frequency in hertz
$x(t)$	Continuous-time signal
$X(j\omega)$	Fourier transform of $x(t)$

Conventions for Discrete-Time Signals and Systems

n	Discrete time step
T	Sampling time, so $t = nT$ where n is an integer
$x(n)$	Discrete-time signal
$X(e^{j\omega T})$	Fourier transform of $x(n)$
$X(n)$	Fourier transform of $x(n)$ at discrete time step n

General Conventions

$\hat{x}$	Real valued amplitude of x or approximation/model of x
x'	Filtered signal
x_∞	Steady state of x
$\bar{x}$	Arithmetic mean of x
σ_x^2	Variance of x
x_{RMS}	Root mean square of x
δx	Virtual signal
$\hat{X}$	Complex amplitude of X or approximation/model of X
X'	Filtered signal
X_∞	Steady state of X
E_x	Mean signal energy
Π_x	Mean signal power
r_{xx}	Auto correlation of x
r_{xy}	Cross correlation between x and y
h	Impulse response of a system
S_{xx}	Auto spectral density of x
S_{xy}	Cross spectral density for x and y
G_{xx}	Single-sided auto spectral density of x
G_{xy}	Single-sided cross spectral density for x and y
H	Transfer function of a system

Conventions for Linear Algebra

Conventions for Scalars

x, X	Scalar variables
X_R	Real part of X, where $X_R = \mathrm{Re}(X)$
X_I	Imaginary part of X, where $X_I = \mathrm{Im}(X)$
X^*	Conjugate complex of X, where $X^* = X_R - jX_I$
$\lvert X\rvert^2$	Squared magnitude of X, where $\lvert X\rvert^2 = X^*X$

Conventions for Column Matrices

$\mathbf{x}$	Lower-case bold variables are column matrices
$\mathbf{x}^T$	The transpose of a column matrix is a row matrix
$\mathbf{x}_R$	Real part of $\mathbf{x}$, where $\mathbf{x}_R = \mathrm{Re}(\mathbf{x})$
$\mathbf{x}_I$	Imaginary part of $\mathbf{x}$, where $\mathbf{x}_I = \mathrm{Im}(\mathbf{x})$
$\mathbf{x}^H$	Hermitian of $\mathbf{x}$, where $\mathbf{x}^H = \mathbf{x}_R^T - j\mathbf{x}_I^T$

$\mathbf{x}^H\mathbf{x}$	The inner product of $\mathbf{x}$, which is a scalar
$\mathbf{x}\mathbf{x}^H$	The outer product of $\mathbf{x}$, whose trace is equal to the inner product
$\|\mathbf{x}\|_2$	Euclidean norm of $\mathbf{x}$, where $\|\mathbf{x}\|_2 = \sqrt{\mathbf{x}^H\mathbf{x}}$

Conventions for Matrices

$\mathbf{X}$	Upper-case bold variables are matrices
$\mathbf{X}^T$	The transpose of $\mathbf{X}$
$\mathbf{X}_R$	Real part of $\mathbf{X}$, where $\mathbf{X}_R = \mathrm{Re}(\mathbf{X})$
$\mathbf{X}_I$	Imaginary part of $\mathbf{X}$, where $\mathbf{X}_I = \mathrm{Im}(\mathbf{X})$
$\mathbf{X}^H$	Hermitian of $\mathbf{X}$, where $\mathbf{X}^H = \mathbf{X}_R^T - j\mathbf{X}_I^T$
$\mathbf{X}^{-1}$	The inverse of $\mathbf{X}$
$\mathbf{X}^{-H}$	The inverse of $\mathbf{X}^H$
$\mathrm{tr}(\mathbf{X})$	Trace of $\mathbf{X}$
$\lambda_i(\mathbf{X})$	The i-th eigenvalue of $\mathbf{X}$
$\|\mathbf{X}\|_2$	Euclidean norm of $\mathbf{X}$, where $\|\mathbf{X}\|_2 = \sqrt{\mathrm{tr}(\mathbf{X}^H\mathbf{X})}$
$\mathbf{I}$	The identity matrix

Conventions for Vectors

$\vec{x}$	Vector valued variable such as position vector
$\vec{x} \cdot \vec{y}$	Scalar product between vectors

Comments on Symbols

Lower-Case Latin Symbols

$\mathbf{b}$	Cost function parameter column matrix
c	Speed of sound or cost function parameter
d	Disturbance or distance between anode and cathode
e	2.718..., error signal, acoustic energy density or additive filtered error
e_{kin}	Acoustic kinetic energy density
e_{pot}	Acoustic potential energy density
f	Frequency
$f_{x(t)}(\xi)$	Probability density function of a stochastic process
f_n	n-th eigenfrequency
f_{nR}	n-th resonance frequency
$\mathbf{f}$	Load column matrix
i	Index, normal component of sound intensity or electric current
$\vec{i}$	Sound intensity vector
j	Index or imaginary number ($j = \sqrt{-1}$)
k	Index, wave number, discrete-time delay or stiffness
k'	Alternative form of complex wave number
k_{nR}	Wave number for the n-th resonance
l	Index or length
m	Index, discrete-time delay or mass
n	Index or discrete time step
$\vec{n}$	Normal vector
p	Acoustic pressure
p_{tot}	Total pressure

p_∞	Equilibrium value of total pressure
p_p	Primary noise
p_s	Anti-noise
q	Source strength, electric charge or volume velocity
r	Damping coefficient or radial distance
$\mathbf{r}$	Residuum column matrix
Δr	Change in radial distance
t	Time
t_i	Observation time point
v	Normal component of acoustic velocity
$\vec{v}$	Acoustic velocity
$\vec{v}_{tot}$	Total value of acoustic velocity
$\vec{v}_\infty$	Equilibrium value of acoustic velocity
$\mathbf{w}$	Column matrix of control filter coefficients
w_{mki}	mki-th control filter coefficient
$\hat{w}_{mki}$	mki-th auxiliary coefficient
x	Signal or x-coordinate
Δx	Separation distance
$\vec{x}$	Position vector
y	Signal or y-coordinate
z	z-coordinate

Upper-Case Latin Symbols

A	Attenuation of analogue filter
$\mathbf{A}$	Cost function parameter matrix
B	Electromagnetic induction
C	Capacity of condenser
$\mathbf{C}$	Stiffness matrix or controller matrix
C_p	Specific heat for constant pressure
C_V	Specific heat for constant volume
D	Dimensionless damping ratio of mechanical systems
$\mathbf{D}$	Damping matrix
E	Error, Energy or Bulk modulus
I	Number of control filter coefficients or instantaneous intensity
$\bar{I}$	Mean intensity
$\bar{I}_M$	Measured mean intensity
$\bar{I}_T$	True mean intensity
J	Number of filter coefficients used for plant modeling or cost function
K	Number of reference signals
L	Number of error signals, length or inductance
M	Number of controller output signals or modal overlap
$\mathbf{M}$	Mass matrix
N	Number of time steps
P_w	Probability of a stochastic process
R	Complex reflection coefficient, electric resistance or residuum
R_Z	Impedance boundary

R_P	Pressure boundary
R_v	Velocity boundary
S	Surface area or cross section
T	Sample time or periodic time or time interval
T_{XY}	Transmissibility between X and Y
T_{60}	Reverberation time
U	Electric voltage
V	Volume
ΔV	Change in volume
$\mathbf{W}_p$	Matrix used to weight the squared sound pressure
$\mathbf{W}_q$	Matrix used to weight the control signal
Z	Acoustic impedance

Lower-Case Greek Symbols

α	Absorption coefficient
α_{nR}	Absorption coefficient for the n-th resonance
β	Weighting factor
χ	Phase angle of complex reflection coefficient
$\delta(t)$	Dirac impulse
ε_{vol}	Volume compression
ε	Filtered error signal for FEFxLMS algorithm
γ	Coherence
κ	Sensitivity, e.g. of microphone
λ	Wave length
λ_i	i-th eigenvalue
μ	Step size
$\tilde{\mu}$	Power normalized step size
ω	Angular frequency
ω_n	Angular frequency corresponding to n-th eigenfrequency
ω_{nR}	Angular frequency corresponding to n-th resonance frequency
ω_M	Modal bandwidth
φ	Phase angle
φ_0	Zero phase angle
$\Delta\varphi_H$	Phase angle between transducers
$\Delta\varphi_p$	Phase angle between two sound pressures
ϕ	Velocity potential
π	3.1415…
ρ	Change in density
ρ_{tot}	Total value of density
ρ_∞	Equilibrium value of density
σ	Decay coefficient
τ	Continuous-time delay
θ	Change in temperature
θ_{tot}	Total value of temperature
θ_∞	Equilibrium value of temperature
ξ	Stochastic process or dimensionless damping ratio in acoustic systems

ξ_{nR}	Damping ratio for the n-th resonance
ζ	Dimensionless frequency ($\zeta = L/\lambda$)

Upper-Case Greek Symbols

Π	Sound power
Σ	Uncertainty

Acronyms

ABN	Airborne noise
ANC	Active noise control
ANS	Active noise system
ACM	Auto correlation matrix
ASAC	Active structural acoustic control
AVC	Active vibration control
ACF	Auto correlation function
ASD	Auto spectral density
BC	Boundary condition
BPF	Blade passage frequency
CA	Coherence analysis
CCF	Cross correlation function
CCM	Cross correlation matrix
CGLS	Conjugated gradient least square
COA	Correlation analysis
CSD	Cross spectral density
DSP	Digital signal processor
DC	Direct current
EBN	External borne noise
EOC	Engine order cancellation
FEM	Finite element method
FeLMS	Filtered error least mean square
FFT	Fast Fourier transform
FIR	Finite impulse response
FRF	Frequency response function
FEFxLMS	Fast exact filtered reference least mean square
FxLMS	Filtered reference least mean square
KHIE	Kirchhoff-Helmholtz integral equation
IBEM	Inverse boundary element method
IBN	Internal borne noise
IFEM	Inverse finite element method
IMC	Internal model control
IMSC	Independent modal space control
IPE	Initial performance estimation
IRA	Impulse response analysis
MA	Military aircraft
MFxLMS	Modified filtered reference least mean square
LMS	Least mean square

LTI	Linear time invariant
MA	Military aircraft
NCP	Normalized cumulative periodogram
NR	Noise reduction
ODE	Ordinary differential equation
PA	Public address
PDE	Partial differential equation
PVP	Principle of virtual pressure
RMS	Root mean square
RSC	Remote sensor control
SBN	Structure borne noise
SPL	Sound pressure level
SIAF	Sound intensity probe with active free field
SVD	Singular value decomposition
THF	Technologiezentrum Hamburg Finkenwerder
TPA	Transducer placement analysis
TR	Tikonov regularization
TVA	Tunable vibration absorber
VLJ	Very light jet
VVS	Volume velocity source
WA	Working area

Contents