Contents

About the Author *xiii*
Preface *xv*
Acknowledgments *xxv*
Glossary *xxvi*
About the Companion Website *xxx*

1 Introduction *1*
1.1 Background *1*
1.2 Spectral Decomposition *4*
1.3 Data Decomposition *6*
1.4 Model-based Decomposition *13*
1.5 Notation and Terminology *24*
1.6 Summary *25*
MATLAB® Notes *26*
References *26*
Problems *27*

2 Random Signals and Systems *31*
2.1 Introduction *31*
2.2 Discrete Random Signals *34*
2.3 Spectral Representation of Random Signals *38*
2.4 Discrete Systems with Random Inputs *41*
2.5 Classical Spectral Estimation *44*
2.5.1 Correlation Method (Blackman–Tukey) *45*
2.5.2 Average Periodogram Method (Welch) *46*
2.5.3 Minimum Variance Distortionless Response (*MVDR*) *48*
2.5.4 Coherence Function *50*
2.6 Case Study: Sinusoids in Noise *52*
2.7 Summary *54*
MATLAB® Notes *55*

References 55
Problems 56

3 Signal Models 61
3.1 Data-Based Models 61
3.1.1 Data-Based Response Matrices 61
3.1.2 Data-Based Toeplitz Matrices 63
3.1.3 Data-Based Hankel Matrices 64
3.2 Parametric-Based Models 65
3.2.1 ARMAX (AR, ARX, MA, ARMA) Models 65
3.2.2 Lattice Models 73
3.2.3 Transfer Function/Frequency Response Function Models 78
3.2.4 Harmonic Models 81
3.3 State-space Models 85
3.3.1 Continuous-time State-space Models 86
3.3.2 Sampled-data State-space Models 88
3.3.3 Discrete-time State-space Models 90
3.3.4 Gauss–Markov State-space Models 92
3.3.5 Innovations Model 95
3.3.6 State-space Equivalence Models 96
3.4 Summary 103
MATLAB® Notes 103
References 104
Problems 105

4 Signal Estimation 111
4.1 Classical Estimation 111
4.1.1 Estimator Properties 113
4.1.2 Estimator Performance 115
4.2 Minimum Variance (MV) Estimation 116
4.3 Maximum A-Posteriori (MAP) Estimation 119
4.4 Maximum Likelihood (ML) Estimation 121
4.5 Least-squares (LS) Estimation 124
4.5.1 Batch Least Squares 124
4.5.2 Recursive Least-squares 128
4.6 Optimal Signal Estimation 133
4.7 Projection Theory 137
4.7.1 Orthogonal Projections: A Geometric Decomposition Perspective 137
4.7.2 Orthogonal Projections: Singular Value Decomposition 140
4.8 Summary 142
MATLAB® Notes 142

References *143*
Problems *144*

5 Signal Decomposition *149*
5.1 Introduction *149*
5.2 Data-Based Decompositions *149*
5.2.1 Data Decomposition: Principal Component Analysis (*PCA*) *151*
5.2.2 Data Decomposition: Independent Component Analysis (*ICA*) *156*
5.2.2.1 Higher Order Statistics *159*
5.2.2.2 Information Theory: Negentropy *160*
5.2.2.3 Information Theory: Mutual Information *161*
5.2.2.4 Estimation Theory: Maximum Likelihood *162*
5.2.3 Data Decomposition: Singular Spectral Analysis (*SSA*) *164*
5.3 Spectral-Based Decompositions *168*
5.3.1 Spectral Decomposition: Multitaper Method (*MTM*) *168*
5.3.2 Spectral Decomposition: Subspace Method *173*
5.3.3 Spectral Decomposition: Pisarenko Harmonic Decomposition (*PHD*) Method *176*
5.3.4 Spectral Decomposition: Multiple Signal Classification (*MUSIC*) Method *177*
5.4 Model-Based Decomposition *179*
5.4.1 Model-Based Decomposition: Damped Exponential Method *180*
5.4.2 Model-Based Decomposition: Lattice Method *186*
5.4.3 Model-Based Decomposition: State-Space Method *192*
5.5 Case Study: Harmonics in Noise *198*
5.6 Summary *201*
MATLAB® Notes *201*
References *202*
Problems *206*

6 Model-based Decomposition: Time Domain *211*
6.1 Background: State-space Systems *211*
6.1.1 Discrete Systems Theory *212*
6.1.2 Stable Linear Systems *214*
6.1.3 Equivalent Linear Systems *215*
6.1.4 Modal Systems *216*
6.2 Realization Problem *220*
6.2.1 Realization Theory *221*
6.2.2 Balanced Realizations *226*
6.2.3 Systems Theory Summary *227*
6.3 Realization Decomposition *228*

6.3.1 Ho–Kalman Realization *228*
6.3.2 SVD Realization *230*
6.4 Subspace Decomposition: Orthogonal Projections *233*
6.4.1 Subspace Realization: Orthogonal Projections *236*
6.4.2 Multivariable Output Error State-space (MOESP) Algorithm *241*
6.5 Subspace Decomposition: Oblique Projections *244*
6.5.1 Subspace Realization: Oblique Projections *248*
6.5.2 Numerical Algorithms for Subspace State-space System Identification (*N4SID*) *250*
6.6 System Order Estimation and Validation *253*
6.6.1 Order Estimation: SVD Approach *255*
6.6.2 Model Validation *257*
6.7 Case Study: Multichannel Mechanical Systems *259*
6.7.1 Mechanical Systems *260*
6.7.2 Case Study: 3-mass Mechanical System *261*
6.8 Summary *267*
MATLAB® Notes *268*
References *268*
Problems *270*

7 Model-Based Decomposition: Frequency Domain *279*
7.1 Introduction *279*
7.1.1 Background *280*
7.2 Frequency Response Functions (*FRF*) *282*
7.2.1 *FRF* Estimation: Impulse Response Method *283*
7.2.2 *FRF* Spectral Estimation: Polynomial Models *285*
7.2.3 *FRF*-Spectral Estimation: Power Spectra *286*
7.2.4 *FRF*-Spectral Estimation: Frequency Domain Decomposition (*FDD*) Method *289*
7.2.4.1 Power Spectral Density Decomposition *289*
7.2.4.2 Complex Mode Indicator Function (*CMIF*) *290*
7.2.5 Stabilization Diagram (*SDIAG*) *292*
7.3 Least-squares Complex Frequency (*LSCF*) Method *295*
7.4 PolyReference Least-Squares Complex Frequency (*pLSCF*) Method *301*
7.5 Maximum Likelihood PolyReference Frequency Domain Estimation (*ML-pLSCF*) *307*
7.6 Case Study: 15-DOF Structure *312*
7.7 Summary *320*
MATLAB® Notes *322*
References *322*
Problems *324*

8 Performance Analysis *329*
8.1 Statistical Performance Methods *329*
8.1.1 Zero-Mean Test *329*
8.1.2 Whiteness Test *330*
8.1.3 Weighted Sum-Squared Residual Test *331*
8.1.4 Standard Error Test *332*
8.1.5 Correlation Coefficient Function Test *332*
8.1.6 Coherence Function Test *333*
8.1.7 Ensemble Tests *334*
8.1.8 Statistical Order Estimation *335*
8.1.9 Signal (Model) Validation *340*
8.1.10 *MAD* Signal Validation *341*
8.2 Physical Performance Metrics *344*
8.2.1 Spectral Peaks: Picking/Histogram *346*
8.2.2 Modal Assurance Criterion (*MAC*) *347*
8.2.3 Hankel/SVD Criteria *348*
8.2.4 Modal Observability Correlation (*MOC*) Criterion *349*
8.2.5 Modal Singular Value (*MSV*) Criterion *349*
8.2.6 Stabilization Diagram (*SDIAG*) *350*
8.2.7 Modal Frequency Tracker *351*
8.3 Case Study: Resonant Modal *MCK* System *352*
8.4 Summary *355*
MATLAB® Notes *355*
References *355*

9 Applications *359*
9.1 Modal Decomposition: Sounding Rocket Flight *359*
9.1.1 Experimental Test Unit Design and Analysis *359*
9.1.2 Sounding Rocket Flight Testing *360*
9.1.3 Summary *367*
9.2 Vibrational Response of a Cylindrical Structure: Identification and Modal Tracking *370*
9.2.1 Summary *376*
9.3 Resonant Ultrasound Spectroscopy *377*
9.3.1 *RUS* Methodology *379*
9.3.2 Modal Analysis: FRF and Frequency Histogram *380*
9.3.3 Model-Based Decomposition Approach *382*
9.3.4 Application: Parallel Piped Structure *382*
9.3.4.1 Synthesized Data: RPP Structure *383*
9.3.5 Experimental Data: RPP Structure *385*
9.3.6 Model-Based Decomposition Processor *388*

9.3.7 Elastic Coefficient Estimation *388*
9.3.8 Summary *390*
9.4 Model-Based Subsystem Decomposition of an 8-Story (8-Mass) Structure *390*
9.4.1 Subspace Structural Identification *391*
9.4.2 Shaping Filters *396*
9.4.3 Subsystem Modal Extraction *397*
9.4.4 Summary *403*
9.5 Data-Based Decomposition: Time-Reversal Processing *403*
9.5.1 Iterative Time-Reversal Decomposition *406*
9.5.2 Eigen-decomposition Time-reversal Extraction *408*
9.5.3 Summary *413*
References *413*

A Probability and Statistics Overview *417*
A.1 Probability Theory *417*
A.2 Gaussian Random Vectors *422*
A.3 Uncorrelated Transformation: Gaussian Random Vectors *423*
A.4 Toeplitz Correlation Matrices *424*
A.5 Important Processes *424*
References *426*

B Projection Theory *427*
B.1 Projections: Deterministic Spaces *427*
B.2 Projections: Random Spaces *428*
B.3 Projection: Operators *429*
B.3.1 Orthogonal (Perpendicular) Projections *429*
B.3.2 Oblique (Parallel) Projections *430*
References *432*

C Matrix Decompositions *433*
C.1 Singular Value Decomposition *433*
C.2 QR Decomposition *435*
C.3 LQ Decomposition *435*
References *436*

Index *437*