INSTRUCTOR MANUAL
for the textbook
STRUCTURAL HEALTH MONITORING WITH PIEZOELECTRIC WAFER ACTIVE SENSORS, Victor Giurgiutiu, Elsevier Academic Press, 2nd Edition, 2014

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1 THE USE OF THE BOOK

This book can be used for

(a) as a textbook for teaching full-length courses as well as short courses
(b) as a research monograph

The various full-length courses and short courses that can be taught using this book are discussed next.

1.1 FULL-LENGTH COURSES

The **full-length courses** to which this book can serve as a textbook fall into several categories:

- **Structural health monitoring** (SHM) with emphasis on active SHM methods. For such a novel course, this book would be the primary textbook, since it is self sufficient for this purpose and contains all the required elements
- **Active materials and smart structures.** For such a novel course, this textbook may need to be complemented with instructor's notes or with reference to other textbooks covering relevant subject matter not covered in this textbook
- Traditional courses on advanced engineering subjects such as, **vibrations**, **wave propagation in solid media**, etc. For such courses, this textbook may need to be complemented with instructor's notes or with reference to other textbooks covering relevant subject matter not covered in this textbook
    - o wave propagation
    - o active materials and smart structures

1.2 SHORT COURSES

Numerous **short courses** can also be taught with this textbook, such as:

- Introduction to structural health monitoring
- Introduction to active materials and smart structures
- E/M Impedance Method for Structural health monitoring
- Wave propagation methods for Structural health monitoring
- In-situ phased arrays for structural health monitoring
- Introduction to vibration
- Introduction to waves in solid media – axial waves
- Introductory vibration of continuous structures– vibrations of bars, beams and shafts
- Intermediate vibration of continuous structures – vibration of plates
- Intermediate waves in solid media – flexural, torsional and 3-D waves
- Guided waves – Rayleigh, SH, Lamb, and pipe waves

1.3 LEVEL OF STUDENT INSTRUCTION

The material contained in this textbook can be used for student instruction at three main levels

- 300-400 level courses for undergraduate students. Depending on the specifics of the academic department, such courses may be **mandatory** or **optional**.
- 500 level courses that are addressed to a mixed audience of undergraduate and graduate students. When planning such courses, the instructor should pay attention to make the requirements for graduate students in the class more challenging than the requirements for the undergraduate students (e.g., extra work on the homework assignments, final exam appropriately targeted, etc.).
- 700-800 for an audience of advanced graduate students. Such courses would require familiarity with advanced mathematical tools and a multidisciplinary knowledge base.

Some of the short course that can be taught from this textbook can be also addressed to advanced-placement (AP) high-school students.

For each instructional level, adequate material selection must be made from the textbook. Table 1 presents the author's suggestion on selecting the material; however, the circumstances of such a selection may vary from school to school and the instructor should accordingly make appropriate selections.

2 LECTURE PLANS

Sample lecture plans for full-length courses and short courses are given below. These lecture plans are not exhaustive; they simply represent the author's suggestions at the time of writing this instructor manual. Further lecture plans may be introduced in updated editions of this web-based document. The reader is encouraged to check the website frequently for possible updates.

2.1 FULL-LENGTH COURSES

A suggested lecture plan for a full-length advanced course on **Structural health monitoring** (SHM) with emphasis on active SHM methods is given in **Error! Reference source not found.**. The course is structured on a 15-week lecture course with three 1-hour lectures per week (MWF schedule). Provision has been made in the schedule for one day of *National Holiday* and two days of *semester break*. The course is structured into twelve major sections, following the twelve chapters of the book. The book sections that can be used for each class are indicated. It should be noted that the allotted time may differ from section to section in accordance to the emphasis given to different topics. The lecture plan provides for two **scheduled tests** and one **final exam**. Impromptu **short quizzes** may be also necessary to test the audience's progress. Such quizzes can be also administered at instructor's discretion.

In planning this schedule, the following **general principles** have been observed:

(a) try to have HMWK due on Mondays
(b) no HMWK on a test week
(c) in the beginning, plan denser HMWK to get students up to speed fast
(d) later in the course, space out the HMWK and make more substantial and difficult
(e) try to avoid overlap between HMWK, tests, and labs, when possible

Twelve **homework assignments** are scheduled in the lecture plan. These homework assignments correspond to the twelve chapters of the book. In each homework, assignments are chosen from the problems and exercises given at the end of each textbook chapter. As a general guidance, the assignments should be chosen in accordance with the instruction level of the course, e.g., introductory, intermediate, and advanced. The lecture plan provided in **Error! Reference source not found.** corresponds to the advanced level.

Five **lab sessions** are scheduled as follows for the following main areas:

1. Vibration
2. Waves
3. PWAS
4. SHM based on vibrations
5. SHM based on wave propagation

The labs may be devised using the practical experiments described in the book. A list of experiments that can be found in the book is given Table 3. Of course, the instructor has the liberty and is also encouraged to develop other experiments illustrating the basic principles described in the theoretical sections.

2.2 SHORT COURSES

A variety of one-week short courses can be taught from this textbook. Several lecture-plan examples are given below. However, several others may be also conceived, and may appear in later editions of this instructor manual. These short courses cover typically five days with three ours in the morning (am) and three hours in the afternoon (pm). The mornings are dedicated to classroom instruction, whereas the afternoons are dedicated to labs and hands-on demos.

2.2.1 Short course: Introduction to Structural Health Monitoring (5 day, high-school AP; university freshman May-semester)

Day	am – Classroom instruction	pm – Labs and demos
Day 1	Structural health monitoring principles. Causes of structural failure and how to prevent it	Group discussion of a major structural failure relevant to the audience
Day 2	Active materials and piezoelectric wafer active sensors (PWAS)	Measurements of PWAS resonators
Day 3	PWAS modal sensors; the electromechanical (E/M) impedance method	Experiments with the E/M impedance method on small beams
Day 4	PWAS wave transducers	Experiments with passive and active use of PWAS wave transducers: impact detection, pitch-catch; pulse-echo
Day 5	Summary and conclusions	Review of experiments and homework Questions and answers session

2.2.2 Short course: Introduction to Active Materials and Smart Structures (5 day, high-school AP; university freshman May-semester)

Day	am – Classroom instruction	pm – Labs and demos
Day 1	Overview of active materials and smart structures	Group discussion of examples of active materials used in everyday life (e.g., piezo lighters) and of the perspective of smart structures improvements on human life
Day 2	Principles of piezoelectricity	Simple piezoelectric experiments/demos. Measurement of direct and converse piezoelectric response.
Day 3	Structure and fabrication of piezoelectric ceramics	Audio-visual instructional material on how piezoceramics are fabricated and tested followed by group discussions
Day 4	Magnetostrictive materials	Experiments with magnetostrictive sensors and actuators
Day 5	Summary and conclusions	Review of experiments and homework Questions and answers session

2.2.3 Short course: Introduction to Vibration (5 days, high-school AP; university freshman May-semester)

Day	am – Classroom instruction	pm – Labs and demos
Day 1	Oscillatory motion Trigonometric, phasor and complex representation Undamped free vibration of a particle	Spring-mass oscillator Mass and stiffness measurements Frequency estimation Frequency measurement Comparison and discussion
Day 2	Damped free vibration Underdamped, critically damped, overdamped vibration Logarithmic decrement Undamped forced vibration	Damped oscillator Estimation of frequency and damping from free oscillations
Day 3	Damped forced vibration Frequency response function Estimation of system damping from the frequency response function	Forced vibration experiment Measurement of frequency response function
Day 4	Dynamic stiffness and mechanical impedance Transmissibility Mechanical-electrical equivalents	Transmissibility experiment Mechanical-electrical equivalents experiment
Day 5	Energy methods in vibration analysis Summary and conclusions	Energy methods experiment Measurement of maximum force Measurement of maximum velocity

2.2.4 Short course: Introduction to Waves (5 day, high-school AP; university freshman May-semester)

Day	am – Classroom instruction	pm – Labs and demos
Day 1	Wave equation D'Alembert solution to wave equation The initial value problem for wave propagation	Spring analogy experiment Simulation of D'Alembert solution Experimentation with various initial values
Day 2	Strain waves and stress waves Particle velocity vs. wave velocity Acoustic impedance of the medium	Instrumented free bar experiment • end impact excitation • piezoelectric excitation Measurement of time of flight for multiple reflections; estimation of wave speed
Day 3	Wave propagation at interfaces Split Hopkinson bar	Split Hopkinson bar experiment Free and built-in reflections
Day 4	Separation of variables solution to the wave equation Harmonic waves Standing waves	Tone-burst propagation in free bar Standing waves identification through frequency sweeps
Day 5	Power and energy: • Axial wave energy • Axial wave power Summary and conclusions	Review of experiments and homework Questions and answers session

Table 1: Textbook material selection suggestion by level of instruction (300-400 represents undergraduate audience; 500 represents combined graduate/undergraduate audience; 700-800 represents advanced graduate audience)

	Instructional level		
	300-400	500	700-800
Chapter 1: Introduction			
1.1 Structural health monitoring principles and concepts	X	X	X
1.2 Structural fracture and failure	X	X	X
1.2.1 Review of linear elastic fracture mechanics principles		X	X
1.2.2 Fracture mechanics approach to crack propagation		X	X
1.3 Aircraft structural integrity program (ASIP0			X
1.3.1 Terminology	X	X	X
1.3.2 Damage tolerance and fracture control		X	X
1.3.3 Component life prediction	X	X	X
1.3.4 Airframe life prediction		X	X
1.3.5 Aircraft usage		X	X
1.3.6 In-service NDI/NDE		X	X
1.3.7 ASIP inspection intervals			X
1.3.8 Fatigue tests and life-cycle prognosis		X	X
1.4 Improved diagnosis and prognosis through structural health monitoring	X	X	X
1.5 About this book	X	X	X
Chapter 2: Electroactive and magnetoactive materials			
2.1 Introduction	X	X	X
2.2 Piezoelectricity	X	X	X
2.2.1 Actuation equations		X	X
2.2.2 Sensing equations			X
2.2.3 Stress equations			X
2.2.4 Actuator equations in terms of polarization			X
2.2.5 Compressed matrix notations	X	X	X
2.2.6 Piezoelectric equations in compressed matrix notations	X	X	X
2.2.7 Relations between the constants	X	X	X
2.2.8 Electromechanical coupling coefficient		X	X
2.2.9 Higher order models of the electroactive response	X	X	X
2.3 Piezoelectric phenomena	X	X	X
2.4 Perovskite ceramics	X	X	X
2.4.1 Spontaneous strain and spontaneous polarization of the Perovskite structure			
2.4.2 Induced strain and induced polarization	X	X	X
2.4.3 Poling of polycrystalline perovskite ceramics		X	X
2.4.4 Common perovskite ceramics	X	X	X
2.4.5 Piezoelectric ceramics	X	X	X

2.4.6 Electrostrictive ceramics	X	X	X
2.4.6.1 Relaxor ferroelectrics		X	X
2.4.6.2 Constitutive equations of electrostrictive ceramics		X	X
2.5 Piezopolymers	X	X	X
2.5.1 Piezopolymers properties and constitutive equations		X	X
2.5.2 Typical piezopolymer applications	X	X	X
2.6 Magnetostrictive materials	X	X	X
2.6.1 Magnetostrictive equations		X	X
2.6.2 Linearized equations of piezomagnetism	X	X	X
2.7 Summary and conclusions	X	X	X
Chapter 3: vibration of solids and structures			
3.1 Introduction	X	X	X
3.2 Single degree of freedom vibration analysis	X	X	X
3.2.1 Free vibration of a 1-dof system	X	X	X
3.2.1.1 Oscillatory motion	X	X	X
3.2.1.1.1 Phasor representation of oscillatory motion	X	X	X
3.2.1.1.2 Complex representation of oscillatory motion	X	X	X
3.2.1.2 Undamped free vibration	X	X	X
3.2.1.2.1 General solution of free undamped vibration	X	X	X
3.2.1.2.2 General solution for given initial displacement and initial velocity	X	X	X
3.2.1.3 Damped free vibration	X	X	X
3.2.1.3.1 General solution of free damped vibration	X	X	X
3.2.1.3.2 Effect of damping on vibration response	X	X	X
3.2.1.3.3 Logarithmic decrement, δ	X	X	X
3.2.1.3.4 Hysteretic damping			
3.2.2 Forced vibration of a particle	X	X	X
3.2.2.1 Undamped forced vibration	X	X	X
3.2.2.1.1 Dynamic amplification factor	X	X	X
3.2.2.2 Damped forced vibration	X	X	X
3.2.2.2.1 Steady-state damped forced vibration solution	X	X	X
3.2.2.2.2 Dynamic stiffness and mechanical impedance		X	X
3.2.2.2.3 Frequency response function	X	X	X
3.2.2.2.4 Estimation of system damping from the frequency response function	X	X	X
3.2.2.2.4.1 Quadrature phase method for damping estimation		X	X
3.2.2.2.4.2 Resonance peak method for damping estimation		X	X
3.2.2.2.4.3 Quality factor method for damping estimation		X	X
3.2.2.2.5 Mechanical-electrical equivalents	X	X	X
3.2.3 Energy methods in 1-dof vibration analysis	X	X	X
3.2.3.1 Undamped 1-dof vibration analysis by energy methods	X	X	X
3.2.3.1.1 Derivation of the equation of motion by energy methods	X	X	X
3.2.3.1.2 Estimation of the natural frequency by energy methods	X	X	X
3.2.3.1.3 Effect of gravitational field on energy methods formulation	X	X	X

of vibration analysis			
3.2.3.2 Damped 1-Dof vibration analysis by energy methods		X	X
3.2.3.2.1 Derivation of the damped 1-dof equation by energy methods		X	X
3.2.3.2.2 Power and energy associated with damped 1-dof response to harmonic excitation		X	X
3.3 Axial vibration of a bar		X	X
3.3.1 Free axial vibration of a pin-pin bar		X	X
3.3.1.1 Natural frequencies		X	X
3.3.1.2 Modeshapes		X	X
3.3.1.3 Orthogonality of modeshapes		X	X
3.3.1.4 Modal mass and stiffness; modal coefficients		X	X
3.3.1.5 Normalization of modeshapes; normal modes		X	X
3.3.1.5.1 Normalization with respect to length		X	X
3.3.1.5.2 Normalization with respect to mass		X	X
3.3.1.6 Orthonormal modes		X	X
3.3.1.7 Rayleigh quotient		X	X
3.3.2 Other boundary conditions		X	X
3.3.2.1 Free-free bar		X	X
3.3.2.2 Fixed-free bar		X	X
3.3.3 Forced axial vibration of a bar		X	X
3.3.3.1 Modal expansion theorem		X	X
3.3.3.2 Modal expansion method for length-normalized modes		X	X
3.3.3.3 Response by modal analysis		X	X
3.3.3.4 Generalized coordinates and modal equations		X	X
3.3.4 Axial vibration energy in a bar		X	X
3.4 Flexural vibration of a beam		X	X
3.4.1 Free flexural vibration of a pin-pin beam		X	X
3.4.1.1 Natural frequencies		X	X
3.4.1.2 Modeshapes		X	X
3.4.1.3 Orthogonality of modeshapes		X	X
3.4.1.4 Modal mass and stiffness; modal coefficients		X	X
3.4.1.5 Normalization of modeshapes; normal modes		X	X
3.4.1.5.1 Normalization with respect to length		X	X
3.4.1.5.2 Normalization with respect to mass		X	X
3.4.1.5 Orthonormal modes		X	X
3.4.2 Other boundary conditions		X	X
3.4.2.1 Free-free beam		X	X
3.4.2.2 Cantilever beam		X	X
3.4.2.3 Numerically-stable flexural modes formulation			X
3.4.2.3.1 Numerically-stable free-free flexural modes			X
3.4.2.3.2 Numerically-stable cantilever flexural modes			X
3.4.3 Forced flexural vibration of a beam		X	X
3.4.3.1 Modal expansion theorem		X	X
3.4.3.2 Modal expansion method for length-normalized modes		X	X

3.4.3.3 Response by modal analysis		X	X
3.4.3.4 Generalized flexural excitation		X	X
3.5 Torsional vibration of a shaft		X	X
3.5.1 Free torsional vibration of a shaft		X	X
3.5.1.1 Natural frequencies and modeshapes modes for fixed-fixed boundary conditions		X	X
3.5.1.2 Other boundary conditions		X	X
3.5.2 Forced torsional vibration of a shaft		X	X
3.5.2.1 Modal expansion theorem.		X	X
3.5.2.2 Response by modal analysis		X	X
3.6 Shear horizontal (SH) vibration of an elastic strip		X	X
3.6.1 Free SH vibration of an elastic strip		X	X
3.6.1.1 Natural frequencies and modeshapes for fixed-fixed boundary conditions		X	X
3.6.1.2 Other boundary conditions		X	X
3.6.2 Forced SH vibration of an elastic strip		X	X
3.6.2.1 Modal expansion method		X	X
3.6.2.2 Response by modal analysis		X	X
3.7 Shear vertical (SV) vibration of a beam		X	X
3.8 Summary and conclusions	X	X	X
Chapter 4: Vibration of plates			
4.1 Introduction		X	X
4.2 Elasticity equations for plate vibrations		X	X
4.3 Axial vibrations of rectangular plates		X	X
4.3.1 Axial vibration equations for rectangular plates		X	X
4.3.2 Axial vibration of square plates			
4.3.3 Straight-crested axial vibration of rectangular plates		X	X
4.4 Axial vibrations of circular plates		X	X
4.4.1 Axial vibration equations for circular plates		X	X
4.4.2 Axisymmetric axial vibration of circular plates		X	X
4.4.2.1 Equation of motion		X	X
4.4.2.2 General solution		X	X
4.4.2.3 Natural frequencies and modeshapes for a free circular plate		X	X
4.4.3 Forced axisymmetric axial vibration of circular plates		X	X
4.4.3.1 Equation of motion		X	X
4.4.3.2 Modal expansion solution		X	X
4.5 Flexural vibrations of rectangular plates		X	X
4.5.1 Flexural vibration equations for rectangular plates		X	X
4.5.1.1 Moments in terms of displacements		X	X
4.5.1.2 Derivation of the equations of motion		X	X
4.5.1.3 Shear forces in terms of displacements		X	X
4.5.1.4 Solution of the equation of motion		X	X
4.5.2 Straight-crested flexural vibration of rectangular plates		X	X
4.5.3 General flexural vibration of rectangular plates		X	X

4.5.3.1 Flexural vibration of simply supported rectangular plates			X
4.5.3.2 Flexural vibration of free rectangular plates			X
4.6 Flexural vibration of circular plates		X	X
4.6.1 Flexural vibration equations for circular plates			X
4.6.1.1 Equation of motion for flexural vibration of circular plates			X
4.6.1.2 General solution for flexural vibration of a circular plate			X
4.6.2 Flexural vibration of free circular plates			X
4.6.3 Axisymmetric flexural vibration of circular plates		X	X
4.6.3.1 Equation of motion		X	X
4.6.3.2 General solution		X	X
4.6.3.3 Natural frequencies and modeshapes for a free circular plate		X	X
4.6.4 Forced axisymmetric flexural vibration of circular plates		X	X
4.6.4.1 Force summation		X	X
4.6.4.2 Moment summation		X	X
4.6.4.3 Equation of motion		X	X
4.6.4.4 Modal expansion solution		X	X
4.7 Summary and conclusions	X	X	X
Chapter 5: Elastic waves in solids and structures	X	X	X
5.1 Introduction	X	X	X
5.2 Overview of elastic wave propagation in solids and structures	X	X	X
5.3 Axial waves in bars	X	X	X
5.3.1 Axial wave equation	X	X	X
5.3.2 D'Alembert solution of the wave equation	X	X	X
5.3.2.1 Change of independent variables	X	X	X
5.3.2.2 Solution in terms of the new independent variables ξ,η	X	X	X
5.3.2.3 D'Alembert solution in terms of the original variable x,t	X	X	X
5.3.2.4 Alternate forms of the d'Alembert solution	X	X	X
5.3.3 Initial value problem of wave propagation	X	X	X
5.3.4 Strain waves and stress waves		X	X
5.3.5 Particle velocity vs. wave speed	X	X	X
5.3.6 Acoustic impedance of the medium	X	X	X
5.3.7 Harmonic waves solution of the wave equation	X	X	X
5.3.8 Standing waves	X	X	X
5.3.9 Power and energy of axial waves	X	X	X
5.3.9.1 Axial wave energy	X	X	X
5.3.9.2 Axial wave power	X	X	X
5.3.9.3 Power and energy of harmonic waves		X	X
5.3.10 Harmonic axial waves at an interface		X	X
5.3.10.1 Interface conditions		X	X
5.3.10.2 Displacement compatibility		X	X
5.3.10.3 Force balance		X	X
5.3.10.4 Interface equations; displacement solution		X	X
5.3.10.5 Stress solution; reflection and transmission coefficients		X	X

5.3.10.6 Special cases		X	X
5.3.10.7 Power and energy transmission through the interface		X	X
5.3.11 Generic axial waves at an interface			X
5.3.11.1 Interface conditions			X
5.3.11.2 Force balance			X
5.3.11.3 Displacement compatibility and particle velocity			X
5.3.11.4 Interface equations			X
5.3.11.5 Interface solution in terms of strain			X
5.3.11.6 Interface solution in terms of stress			X
5.4 Flexural waves in beams		X	X
5.4.1 Flexural waves equation		X	X
5.4.2 Dispersion of flexural waves		X	X
5.4.3 Group velocity		X	X
5.4.3.1 Definition of group velocity		X	X
5.4.3.2 Group velocity of flexural waves		X	X
5.4.4 Energy velocity		X	X
5.4.5 Power and energy of flexural waves in a beam		X	X
5.4.5.1 Flexural wave energy		X	X
5.4.5.2 Flexural wave power		X	X
5.4.6 Flexural waves at an interface			X
5.4.6.1 Interface conditions			X
5.4.6.2Wave derivatives			X
5.4.6.3 Interface equations and their solution			X
5.4.6.4 Power balance across the interface			X
5.5 Torsional waves in a shaft		X	X
5.6 Shear horizontal (SH) waves in a strip		X	X
5.7 Shear vertical (SV) waves in a beam		X	X
5.8 Plate waves		X	X
5.8.1 Axial waves in plates		X	X
5.8.1.1 Equation of motion for axial waves in plates		X	X
5.8.1.2 Straight-crested axial waves in plates		X	X
5.8.1.3 Straight-crested shear waves in plates		X	X
5.8.1.4 Circular-crested axial waves plate in plates		X	X
5.8.2 Flexural waves in plates		X	X
5.8.2.1 Equation of motion for flexural waves in plates		X	X
5.8.2.2 Straight-crested flexural waves in plates		X	X
5.8.2.3 Circular-crested flexural waves in plates		X	X
5.8.3 Shear horizontal (SH) waves in a plate		X	X
5.8.4 Torsional waves in a plate (circular crested SH waves)		X	X
5.9 Plane, spherical, and circular wave fronts		X	X
5.9.1 Plane waves		X	X
5.9.1 Generic plane waves		X	X
5.9.1Harmonic plane waves		X	X
5.9.2 Spherical waves		X	X
5.9.2.1 Generic spherical waves		X	X

5.9.2.2 Harmonic spherical waves		X	X
5.9.3 Circular and cylindrical waves		X	X
5.9.3.1 Generic circular and cylindrical wave		X	X
5.9.3.2 Harmonic circular and cylindrical waves		X	X
5.10 Bulk waves in an infinite elastic medium			X
5.10.1 Eigenvalues of the wave equations; fundamental wave speeds			X
5.10.2 Eigenvectors of the wave equations			X
5.10.3 Wave potentials			X
5.10.4 Dilatational and rotational waves			X
5.10.5 Irrotational and equivolume waves			X
5.10.6 z-invariant			X
5.11 Summary and conclusions	X	X	X
Chapter 6: Guided waves			
6.1 Introduction	X	X	X
6.2 Rayleigh surface waves		X	X
6.2.1 Rayleigh surface wave equations		X	X
6.2.2 Boundary conditions		X	X
6.2.3 Wave speed of the Rayleigh surface wave		X	X
6.2.4 Particle motion of the Rayleigh surface wave		X	X
6.3 SH plate waves			X
6.3.1 SH wave equation			X
6.3.2 Boundary conditions			X
6.3.2.1 Symmetric SH modes			X
6.3.2.2 Antisymmetric SH modes			X
6.3.3 Dispersion of SH waves			X
6.3.3.1 Wave speed dispersion curves			X
6.3.3.2 Cut-off frequencies			X
6.3.3.3 Significance of imaginary wave numbers; evanescent waves			X
6.3.3.4 Group velocity dispersion curves			X
6.4 Lamb waves			X
6.4.1 Lamb waves equations			X
6.4.2 Solutions of the Lamb wave equations; dispersion curves			X
6.4.2.1 Symmetric solution of the Lamb wave equations			X
6.4.2.2 Antisymmetric solution of the Lamb wave equations			X
6.4.3 Lamb wave modes			X
6.4.3.1 Symmetric Lamb wave modes			X
6.4.3.2 Antisymmetric Lamb wave modes			X
6.4.4 Lamb wave group velocity			X
6.4.5 Section summary			X
6.5 Circular crested Lamb waves			X
6.5.1 Circular crested Lamb equations			X
6.5.2 Pressure Potential For Circular Crested Lamb waves			X
6.5.3 Shear Potential For Circular Crested Lamb waves			X
6.5.4 Coherence condition			X

6.5.5 Displacement and stresses in terms of potentials			X
6.5.5.1 Calculation of dilatation			X
6.5.5.2 Calculation of strains			X
6.5.5.3 Calculation of stresses in terms of potentials			X
6.5.5.4 Calculation of stresses in terms of the unknowns A_1, A_2, B_1, B_2			X
6.5.6 Solution of the Lamb wave equation			X
6.5.6.1 Symmetric solution of the Lamb wave equation			X
6.5.6.2 Antisymmetric solution of the Lamb wave equation			X
6.5.7 Circular crested Lamb wave modes			X
6.5.7.1 Symmetric circular crested Lamb wave modes			X
6.5.7.2 Antisymmetric circular crested Lamb wave modes			X
6.5.8 Asymptotic behavior of circular crested Lamb waves			X
6.5.9 Section summary			X
6.6 General formulation of guided waves in plates			X
6.7 Guided waves in tubes and shells			X
6.7.1 Derivation of guided waves equations for cylindrical shells			X
6.7.2 General solution for guided waves in cylindrical shells			X
6.7.3 Guided-wave modes in cylindrical shells			X
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15.2.2 Damage detection with damage metrics		X	X
15.2.3 Damage detection with statistical methods		X	X
15.2.3.1 Inherent statistical variation in the E/M impedance data		X	X
15.2.3.2 Damage detection using feature based statistics			X
15.2.3.3 The use of the t-test for damage identification			X
15.2.4 Damage detection with probabilistic neural nets			X
15.2.4.1 PNN with four inputs		X	X
15.2.4.2 PNN with six inputs		X	X
15.2.4.3 PNN with eleven inputs		X	X
15.2.5 Section summary	X	X	X
15.3 Case study 2: damage detection in aging aircraft-like panels	X	X	X
15.3.1 Description of the aging aircraft-like panel specimens	X	X	X
15.3.2 Pulse-echo crack detection in aging aircraft-like panels	X	X	X
15.3.2.1 Pulse-echo PWAS signals reflected by structural features		X	X
15.3.2.2 Change in pulse-echo PWAS signal due to crack presence	X	X	X
15.3.2.3 Signal differential method for separation of damage-related echoes			
15.3.3 E/M impedance damage detection in aging aircraft-like panels	X	X	X
15.3.3.1 Damage metric classification in the PWAS near field		X	X
15.3.3.2 Damage metric classification in the PWAS medium field		X	X
15.3.3.3 PNN classification in the PWAS medium field and PWAS near field		X	X
15.3.4 Section summary	X	X	X
15.4 Summary and conclusions	X	X	X
Appendix A: Mathematical prerequisites		X	X
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A.1.1 Fourier series of periodic signal		X	X
A.1.2 Fourier transform of aperiodic signal		X	X
A.1.3 Discrete time Fourier transform		X	X
A.1.3.1 N-point discrete Fourier transform		X	X

A.1.3.2 Definition 1: from DTFT to DFT		X	X
A.1.3.3 Definition 2: direct definition		X	X
A.1.4 Discrete Fourier transform analysis of pulse and sinusoid signals		X	X
A.1.4.1 DTFT of rectangular signal		X	X
A.1.4.2 DTFT and DFT of q-point shifted rectangular signal $x[n]=p[n-q]$		X	X
A.1.4.3 DTFT of discrete cosine signal		X	X
A.1.4.4 N-point DFT of discrete cosine signal $x[n]$		X	X
A.1.5 Investigation of DFT spectrum leakage		X	X
A.1.5.1 Case study of the leakage phenomenon		X	X
A.1.5.2 Discussion		X	X
A.2 Sampling theory		X	X
A.2.1 Impulse-train sampling		X	X
A.2.2 The sampling theorem		X	X
A.3 Convolution		X	X
A.3.1 Discrete time signal convolution		X	X
A.3.2 Continuous time convolution		X	X
A.3.3 Properties of convolution		X	X
A.4 Hilbert transform		X	X
A.5 Correlation method		X	X
A.6 Time averaged product of two harmonic variables		X	X
A.7 Orthogonal properties of harmonic functions		X	X
A.8 Bessel and Hankel functions			X
A.8.1 Bessel functions			X
A.8.2 Hankel functions			X
A.8.3 Modified Bessel functions			X
A.8.4 Properties of Bessel and Hankel functions			X
A.8.4.1 Properties of Bessel functions at the origin			X
A.8.4.2 Recurrence properties of Bessel and Hankel functions			X
A.8.4.3 Odd and even properties of J_ν Bessel functions			X
A.8.4.4 Differentiation properties of Bessel and Hankel functions			X
A.8.4.5 Conversion, recurrence, and differentiation properties of modified Bessel functions			X
A.8.5 Asymptotic behavior of Bessel and Hankel functions			X
A.8.5.1 Asymptotic behavior of Bessel functions			X
A.8.5.2 Asymptotic behavior of Hankel functions			X
A.8.6 Orthogonality of Bessel and Hankel functions			X
A.8.7 Normality of Bessel functions			X
A.8.7.1 Norm of J_ν			X
A.8.7.2 Norm of J_0			X
A.8.7.3 Norm of J_1			X
A.8.8 Hankel transform			X

A.9 Matrix and linear systems	X	X	X
A.9.1 Inverse of a 2×2 matrix	X	X	X
A.9.2 Solution of a 2×2 linear system	X	X	X
Appendix B: Elasticity notations and equations			
B.1 Basic notations			
B.1.1 Basic Cartesian vector notations and differential operators		X	X
B.1.2 Basic tensor notations		X	X
B.2 3–D strain–displacement relations		X	X
B.2.1 Cartesian Notations		X	X
B.2.2 Tensor notations		X	X
B.3 Dilatation and rotation			X
B.3.1 Dilatation			X
B.3.2 Rotation			X
B.3.2.1 Cartesian notations			X
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B.3.2.3 Vector notations			X
B.4 3–D stress–strain relations in engineering constants		X	X
B.5 3–D stress–strain relations in Lame constants			X
B.5.1 Cartesian notations			X
B.5.2 Tensor notations			X
B.6 3–D stress–displacement relations			X
B.6.1 Cartesian notations			X
B.6.2 Tensor notations			X
B.7 3–D equations of motion		X	X
B.7.1 Cartesian notations			X
B.7.2 Tensor notations			X
B.8 3–D governing equations – Navier equations			X
B.8.1 Cartesian notations			X
B.8.2 Vector notations			X
B.8.3 Tensor notations			X
B.9 Tractions			X
B.9.1 Cartesian notations			X
B.9.2 Tensor notations			X
B.9.3 Relation between tractions and displacements			X
B.10 Boundary conditions			X
B.10.1 Dirichlet boundary conditions			X
B.10.2 Neumann boundary conditions			X
B.10.3 Cauchy boundary conditions			X
B.10.4 Robin boundary conditions			X
B.10.5 Mixed boundary conditions			X
B.11 2–D elasticity		X	X
B.11.1 Plane–stress conditions		X	X
B.11.2 Plane–strain conditions		X	X
B.12 Plane-stress elasticity in polar coordinates		X	X

B.12.1 Coordinates transformation		X	X
B.12.2 Basic differential operations and operators			X
B.12.3 Strain–displacement relations			X
B.12.4 Equations of motion			X
B.12.5 Stress–strain relation			X
B.12.6 Stress-displacement relation			X
B.13 Cylindrical coordinates			X
B.13.1 Coordinates transformation			X
B.13.2 Basic differential operations and operators			X
B.13.3 Strain–displacement relations			X
B.13.4 Equations of motion			X
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B.13.6 Governing equations – Navier-Lame Equations			X
B.14 Axisymmetric polar and cylindrical coordinates			X
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B.14.1.1 Basic differential operations and operators			X
B.14.1.2 Strain-displacement relations			X
B.14.1.3 Equations of motion			X
B.14.1.4 Stress-strain relation			X
B.14.1.5 Stress-displacement relation			X
B.14.2 Axisymmetric elasticity in cylindrical coordinates			X
B.14.2.1 Basic differential operations and operators			X
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B.14.2.3 Equations of motion			X
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B.14.2.5 Governing equation – Navier-Lame equations			X
B.15 Spherical coordinates			X
B.15.1 Coordinates transformation			X
B.15.2 Basic differential operations and operators			X
B.15.3 Strain–displacement relations			X
B.15.4 Equations of motion			X
B.15.5 Stress–strain relation			X
B.15.6 Governing equations – Navier-Lame equations			X

: MWF schedule

Table 2: Sample teaching plan for a full-length course

ADVANCED STRUCTURAL HEALTH MONITORING

wk	Class Topics	Book section	Hmwk	Lab
1	SHM overview	Ch. 1		
	Active materials	2.1; 2.2		
		2.3, 2.4		
2		2.5, 2.6	Hw1	Lab orientation
	National Holiday. no classes			
	Vibrations review	3.1; 3.2		
3		3.3; 4.4	Hw2	**Lab #1**
		4.6		
	Waves review	5.1; 5.2; 5.3.1--3		
4		5.3.4--11	Hw3	
		5.4		
		5.8; 5.10		
5		6.1; 6.2	Hw4	
		6.3		
		6.4		
6		6.5	Hw5	**Lab #2**
	PWAS basics	7.1—7.3		
		7.4—7.7		
7	PWAS coupling with structure	8.1; 8.2; 8.4	Hw6	
	Test review			
	Test #1			
8	PWAS resonators	9.1; 9.2	Hw7	
		9.3		
		9.5		
9	Vibration SHM: E/M impedance method	10.1; 10.2.	Hw8	**Lab #3**
		10.3		
		10.4; 10.5		
10	Semester break. no classes			
	Semester break. no classes			
	Wave tuning with PWAS	11.1; 11.1; 11.2		
11		11.3; 11.4	Hw9	
		11.5; 11.7		
	Test review			
12	**Test #2**			**Lab #4**
	Wave Propagation SHM	12.1; 12.2		
		12.3—12.5		
13		12.6—12.8	Hw10	
	PWAS phased arrays	13.1—13.3		
		13.4—13.7		
14		13.8—13.10	Hw11	
	Signal processing	14.1; 14.2		
		14.3—14.7		
15	Case studies	15.1; 15.2	Hw12	**Lab #5**
		15.3; 15.4		
	Final review and course summary			
E	**Final exam**			

Notes: (a) try to have HMWK due on Mondays; (b) no HMWK on a test week; (c) in the beginning, denser HMWK to get students up to speed fast;(d) later, space HMWK out; (e) try to avoid overlap between HMWK, tests, and labs, when possible

Table 2: List of experiments that are described in the book

Page	experiment
52	particle vibration
367-570	directivity patterns of high-aspect-ratio rectangular PWAS
385	self-diagnosis of PWAS transducers
386	temperature cycling of PWAS
388	environmental exposure of PWAS
389	submersion exposure of PWAS
390	large strain testing of PWAS
390-391	fatigue testing of PWAS
466-470	rectangular PWAS resonators
486	circular PWAS resonator
489	square PWAS resonator
553-561	tuning of square and circular PWAS on thin and thick plates
562-566	directional tuning of rectangular PWAS of high aspect ratio: directivity
590-594	PWAS modal sensors (E/M impedance method) on small steel beams
595	PWAS modal sensors (E/M impedance method) on turbo-engine blade
604-606	PWAS modal sensors (E/M impedance method) on circular plates
608	Damage detection and propagation in spot-welded lap joint with PWAS modal sensors (E/M impedance method) during fatigue loading
613-615	Bonded joints damage detection with PWAS modal sensors (E/M impedance method) in thin plates
617	Bonded joints damage detection with PWAS modal sensors (E/M impedance method) in space panels
618-619	Bonded joints damage detection with PWAS modal sensors (E/M impedance method) in adhesively bonded rotor blade structure
622-625	Detection of disbond presence and progression in bonded composite overlays on concrete coupon specimens using PWAS modal sensors and E/M impedance spectroscopy
625-629	Detection of disbond presence and progression in bonded composite overlays on full-scale concrete beam using PWAS modal sensors and E/M impedance spectroscopy
652-653	1-D wave propagation PWAS experiments
662-663	1-D wave propagation PWAS experiments (cont.)
663-664	Rayleigh wave propagation PWAS experiments on rail-road track rail
665-667	2-D wave propagation PWAS experiments setup
667-668	Pitch-catch PWAS experiments in a plate
669-671	Pulse-echo PWAS experiments in a plate
674-675	Pitch-catch PWAS detection of crack growth in a plate
679-680	Pulse-echo PWAS detection of crack growth in composite beam
891-894	Pulse-echo PWAS crack detection in aging aircraft panel
686-689	PWAS time-reversal experimental setup and Lamb wave mode tuning
690-691	PWAS time reversal of A0 and S0 Lamb waves
691-692	PWAS time reversal of S0+A0 Lamb waves
697-698	Impact detection with PWAS transducers
699-700	Acoustic emission detection with PWAS transducers

724-728	Simple phased-array experiment with a 1-D linear PWAS array
728-729	Pin-hole detection with PWAS linear array using the EUSR phased-array algorithm
729	Broad-side crack detection with PWAS linear array using the EUSR phased-array algorithm
729-730	Sloped broad-side crack detection with PWAS linear array using the EUSR phased-array algorithm
730	Single offside crack detection with PWAS linear array using the EUSR phased-array algorithm
731	Detection of two broadside cracks with PWAS linear array using the EUSR phased-array algorithm
731-732	Detection of three in-line broadside cracks with PWAS linear array using the EUSR phased-array algorithm
733-734	Crack detection on curved panels with PWAS linear array using the EUSR phased-array algorithm
739-743	In-situ direct imaging of crack growth with PWAS phased arrays and EUSR algorithm
755-756	Effect of array weight functions on broadside crack detection with PWAS linear phased array
785-786	2-D phased array detection of broadside crack using a 4×8 PWAS phased array and 2D-EUSR algorithm
788	Offside-crack 2-D phased array detection using a 4×8 PWAS phased array and 2D-EUSR algorithm
788-790	2-D phased array detection of broadside crack using an 8×8 PWAS phased array and 2D-EUSR algorithm
820	Short time Fourier transform analysis of an experimental PWAS pulse-echo signal
828-829	Narrow-band filtering of an experimental PWAS pulse-echo signal using continuous wavelet transform and comparison with short time Fourier transform
841	Denoising of an experimental signal using the discrete wavelet transform
844	Denoising of an experimental signal using the discrete wavelet transform
866-871	Spectral measurements with PWAS modal sensors (E/M impedance method)
873-874	Damage detection in circular plates with PWAS modal sensors (E/M impedance method) using damage metrics
881-886	Damage detection in circular plates with PWAS modal sensors (E/M impedance method) via the probabilistic neural networks approach
895-898	Near-field damage detection in aging aircraft panels using PWAS modal sensors and E/M impedance method with damage metrics
900-902	Medium-field damage detection in aging aircraft panels using PWAS modal sensors and E/M impedance method and probabilistic neural networks. Same approach also applied to near-field damage
877-879	Damage detection in circular plates by processing with the statistical t-test the third frequency measured with PWAS modal sensors
882-886	Details of the feature extraction and probabilistic neural network processing of the experimental spectra measured with PWAS modal sensors on circular plates

900-902 Details of the feature extraction and probabilistic neural network processing of the experimental spectra measured with PWAS modal sensors on aging aircraft-like panel