Analysis of Wave Propagation in Structures and Solids

PhD course at the International Doctoral School of Engineering and Science
Aalborg University, 16-23 August 2017

The course concerns the physics and modelling of wave propagation in structures and solids. The theories and formulations covered by the course are applicable within structural and mechanical engineering as well as earthquake and geotechnical engineering. Firstly, an introduction is given to the basic properties of body waves in an elastic continuum. Phenomena such as geometrical and material dissipation, dispersion, impedance, reflection and refraction are discussed. Furthermore, the formulation of theories for wave propagation in one-dimensional structures, including straight and curved beams, plates and cylindrical shells, is considered. The Floquet theory for periodic structures is introduced and exemplified. Secondly, the finite element method is introduced as a computational tool for the analysis of wave propagation in soil and structures. Special attention is paid to its wave format for modelling one- and two-dimensional piecewise homogeneous/periodic structures. Time and frequency-domain solutions are considered, and guidelines are given for the treatment of artificial boundaries in numerical models. Thirdly, boundary integral equations and boundary-element schemes for wave propagation in solids and structures are derived in the frequency domain, and an alternative solution for stratified materials, e.g. layered soil, is given in the wavenumber-frequency domain. Finally, lumped-parameter models (LPMs) are introduced as a means of representing the dynamic stiffness of continuous structures and soil in a computationally efficient manner. As an example, the application of LPMs for wind-turbine or machine foundations is illustrated.

Organizers: Lars V. Andersen, Associate Professor (phone: +45 9940 8455; e-mail: la@civil.aau.dk).
Sergey V. Sorokin, Professor (phone: +45 9940 9332; e-mail: svs@me.aau.dk).

Lecturers: Lars V. Andersen, Associate Professor of Geotechnical Engineering, Aalborg University;
Sergey V. Sorokin, Professor of Vibro-Acoustics, Aalborg University;
Elisabetta Manconi, Guest Lecturer, University of Parma, Italy.

Workload: 5 ECTS

Time: 16–23 August 2017

Venue: Aalborg University, Aalborg Main Campus, Room to be announced.

Prerequisites: The participant must have a solid background in continuum mechanics and partial differential equations. Experience with numerical methods and programming is strongly recommended. The participants are expected to read the texts in the literature list before the course. The literature will be available upon registration.

Form: Each part of the course consists of a lecture followed by a workshop. All lectures are given in English.

Evaluation: As part of the course work, the participant must hand in a portfolio containing answers to exercises as well as computer codes elaborated by the participant during and after the course. Some of this work may be carried out in the workshops.

Lecture Plan

Day 1 — 16 August 2017

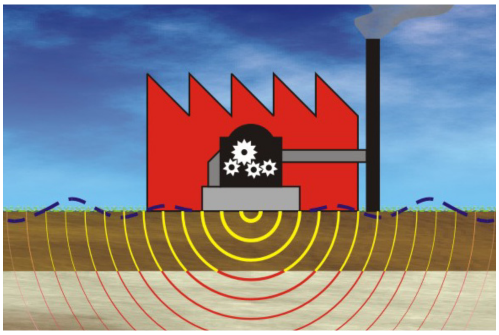
Morning class
09:00 – 12:00

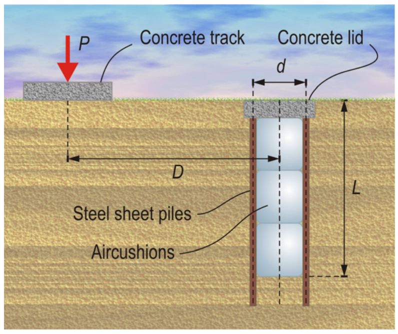
The basics of elastodynamics – Part 1
Applications of elastodynamics. Body waves in an elastic solid: P- and S-waves. Surface waves. Mechanical impedance. Reflection and refraction at interfaces and surfaces. Exercise 1 in [1].

Lecturer: Lars V. Andersen **Literature:** [1] Chapter 1

Afternoon class
13:00 – 16:00

The basics of elastodynamics – Part 2
Dispersion and dissipation of waves. Cut-on/cut-off frequencies. Geometrical and material damping. Viscoelastic constitutive models. Introduction to Green's functions for body waves in an elastic solid. Exercise 2 in [1].





Lecturer: Lars V. Andersen **Literature:** [1] Chapter 1

Day 2 — 17 August 2017

Morning class
09:00 – 12:00

Wave propagation in one dimensional structures
Dilatation waves, torsion waves and flexural waves in straight rods (elementary theories). Timoshenko beam analysis. Wave propagation in curved and non-uniform structures.

Lecturer: Sergey Sorokin **Literature:** [2] Sections 1.4, 1.14-1.16; [3] Chapters 1-2

Afternoon class
13:00 – 16:00

Mini symposium
PhD students must give a presentation of their research project. Depending on the number of participants, the presentations should be 10-20 minutes. After each presentation there will be time for discussion.

Moderators: Lars V. Andersen and Sergey Sorokin

Day 3 — 18 August 2017

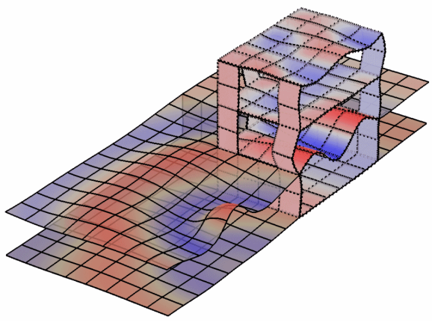
Morning class
09:00 – 12:00

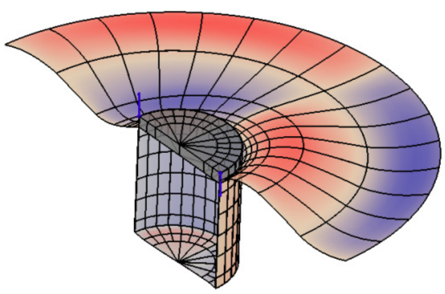
Boundary integral equations for stationary waves in elastic rods
The boundary integral equation method. Green's function and Somigliana's identity: Axial waves in a rod; flexural waves in a beam. Wave propagation, reflection and transmission in elastic rods. Exercises in [2], 1.11-1.12

Lecturer: Sergey V. Sorokin **Literature:** [2] Sections 1.9-1.13, 1.17-1.22

Afternoon class
13:00 – 16:00

Introduction to the boundary-element method in elastodynamics
Boundary integral equations. Green's functions for displacements and stresses. Boundary elements for two and three-dimensional analysis. Frequency domain solutions. Coupling with finite-element schemes.





Lecturer: Lars V. Andersen **Literature:** [1] Chapter 3

Day 4
21 August 2017

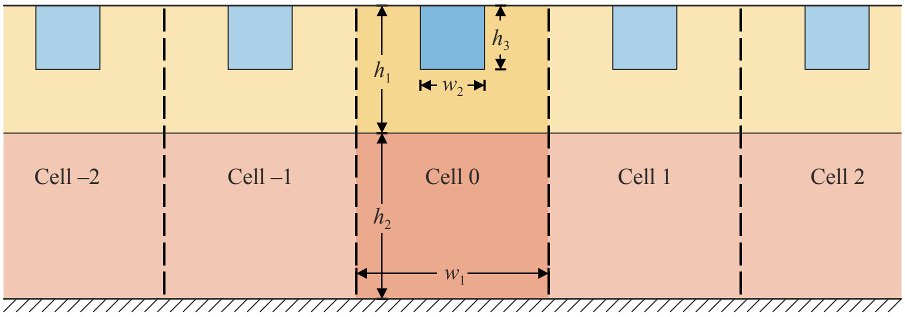
Morning class
09:00 – 12:00

The domain-transformation method for stratified elastic solids
Introduction. Response of a layered half-space. Flexibility matrix for a layered half-space. Computational optimisations. Dispersion of waves in a stratum. Applications to earthquake engineering and foundations. Exercise 4 in [1].

Lecturer: Lars V. Andersen — **Literature:** [1] Chapter 5

Afternoon class
13:00 – 16:00

Wave propagation in periodic structures
Floquet theory. Stop and pass frequency bands in infinite periodic straight rods: dilatation and flexural waves. Effect of a finite number of 'periodicity cells'. Periodic springs.



Lecturer: Sergey V. Sorokin — **Literature:** [2]

Day 5
22 August 2017

Morning class
09:00 – 12:00

The finite-element method and wave analysis – Part 1
Basic steps of the finite-element method: Beam, shell and continuum models. Discretization considerations regarding space and time. Finite element analysis of unbounded domains and infinite structures. Exercise 3 in [1].

Lecturer: Elisabetta Manconi — **Literature:** [4], [5]

Afternoon class
13:00 – 16:00

The finite-element method and wave analysis – Part 2
Basic approach of wave and finite element analysis – examples for rods and beams. Use of the method for the plate-strip to illustrate the method for waveguides. Examples given for a car tyre.

Lecturer: Elisabetta Manconi — **Literature:** [6], [7]

Day 6
23 August 2017

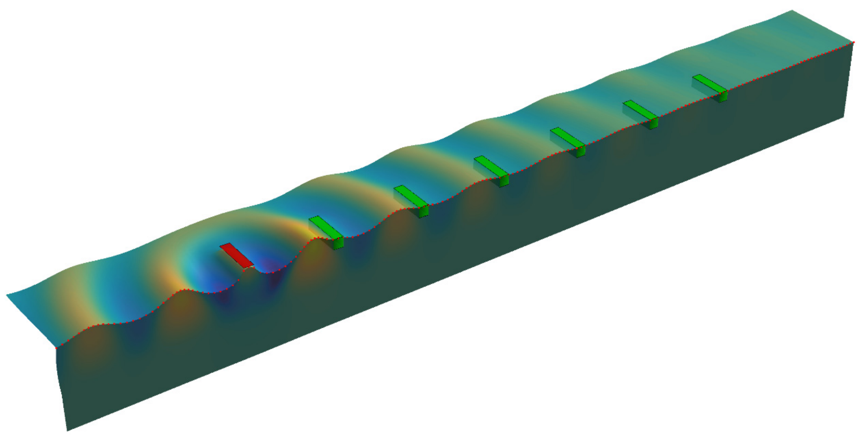
Morning class
09:00 – 12:00

Lumped-parameter models for dynamic structures and solids
Introduction and motivation. Standard and fundamental models. Consistent models: Fitting and implementation in finite-element codes. Application to the analysis of wind-turbine and machine foundations.

Lecturer: Lars V. Andersen — **Literature:** [1] Chapter 6

Afternoon class
13:00 – 16:00

Workshop
The last day of the course, we will discuss the exercises. Participants will have time to work on the solutions under the supervision of the lecturers.



Supervisors: Lars V. Andersen, Sergey Sorokin and Elisabetta Manconi

Literature

[1] Lars Andersen (2006). “Linear Elastodynamic Analysis”, DCE Lecture Notes No. 3. Aalborg University, Department of Civil Engineering, December 2006.

[2] Sergey Sorokin (2007). Basics of the Theory of Wave Propagation in Elastic Structures, Lecture Notes, Aalborg University, Department of Mechanical Engineering.

[3] Sergey Sorokin (2004). An Introduction to the Theory of Wave Propagation in Elastic Cylindrical Shells Filled with an Acoustic Medium, Pre-print of the Centre of Machine Acoustics, Aalborg University, Department of Mechanical Engineering.

[4] B. R. Mace, E. Manconi, Modelling wave propagation in two-dimensional structures using finite element analysis, Journal of Sound and Vibration, 318, 884-902, 2008.

[5] F. Fahy and P. Gardonio (2006). “Sound and Structural Vibration: Radiation, Transmission and Response”, Academic Press; 2 edition 2006.

[6] E. Manconi, B. R. Mace, Wave characterization of cylindrical and curved panels using a finite element method, Journal of the Acoustical Society of America, 125, 154-163, 2009.

[7] J. M. Renno, E. Manconi, B. R. Mace, A Finite Element Method for Modelling Waves in Laminated Structures, Advances in Structural Engineering, 16, 61-75, 2013.