ME 59700/ME 60602: TOPOLOGY OPTIMIZATION
Department of Mechanical and Energy Engineering
Indiana University-Purdue University Indianapolis

Instructor Information

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Course Information

Name: Topology Optimization ME 59700
Temporary code (used until 2020): ME 59700
Permanent code (used from 2021): ME 60602
Number of credit hours: 3.0

About this course

This graduate-level course focuses on theoretical and practical aspects of numerical methods utilized in the solution of finite element-based structural optimization problems with emphasis on topology optimization. Topology optimization is a numerical method to synthesize high-performance, free-form structures by optimally distributing material within a loosely defined volume (design domain) with given set of boundary conditions, e.g., external loads and supports, without any preconceived shape. This freedom provides topology optimization with the ability to find innovative, complex, lightweight, organic structural layouts that have found applications in aerospace, automotive, biomedical, architecture and civil engineering among other fields. Topology optimization constitutes an active area of research in applied mathematics and engineering, which has been enhanced by advanced manufacturing methods such as additive manufacturing. Today, computer-aided engineering (CAE) commercial software tools have incorporated topology optimization capabilities along with traditional finite-element analysis. The rapidly expanding field of topology optimization has important applications in mathematics, mechanics, and materials. Topology optimization also has an important impact on manufacturing industries and is likely to have a significant role in micro- and nano-technologies. Therefore, it is relevant for any mechanical engineer to understand the theoretical aspects of topology optimization as well as the scope and current areas of research and development.

The goal of this course is to understand the mathematical and numerical background required to solve topology optimization problems. Students of this course will be exposed to the development of numerical methods for finite element analysis of discrete (truss) and continuous (2D and 3D) structures, sensitivity analysis methodologies, and specialized gradient-based optimization methods as well as applications that include the design of lightweight structures, compliant mechanisms, and heat conduction applications. Additional topics include the design of multi-phase (porous) and multi-materials structures. Students of this class will be exposed to relevant journal papers. At the completion of this course, students will be able to understand state-of-the-art literature in topology optimization.

After completion of this course, the students should be able to:

- Develop finite element code for topology optimization of discrete and continuum structures.
- Apply sensitivity analysis methods including direct and adjoint methods.
- Implement optimization algorithms including SQP and MMA.
- Address computational issues such as uniqueness, checkerboards, and mesh dependency.
- Develop algorithms to design structure with a lattice (porous) internal structure.
- Apply topology optimization methods to solve problem involving non-compliant structures, compliant mechanisms, and thermal loads in 2D and 3D structures.

Prerequisites

This class is offered to graduate students holding a B.S. degree in Engineering, Physics, Mathematics, or related. Undergraduate students can also take this class after their completion of any ME 400-level course or equivalent.

The course builds on two main graduate-level courses: ME 50601 (Design Optimization Methods) and ME 55100 (Finite Element Analysis). Students taking this course should also have a strong mathematical background, which is offered in graduate-level math courses.

Recommended (non-mandatory) courses that provide a stronger background for topology optimization include:

- ME 47200 (Advanced Mechanics of Materials)
- ME 55100 (Finite Element Analysis)
- ME 58100 (Numerical Methods in Mechanical Engineering)
- ME 50601 (Design Optimization Methods)

References

Required book:

- [Opt] Peter W. Christensen and Anders Klarbring, An Introduction to Structural Optimization, Springer, 2008, ISBN: 1402086660, 9781402086663.

Recommended book:

- [FEA] Ferreira, A.J.M., MATLAB Codes for Finite Element Analysis, Springer, 2009

Additional books:

- Haftka, R.T. and Z. Gurdal, Elements of Structural Optimization, 3rd edition, Springer, 1992.
- Haug, E.J., K.K. Choi and V. Komkov, Design Sensitivity Analysis of Structural Systems, Academic Press, 1986.
- Bendsoe, M.P and O. Sigmund, Topology Optimization: Theory, Methods, and Applications, 3nd edition, Springer, 2003

Online resources:

- K. Liu and A. Tovar, An efficient 3D topology optimization code written in Matlab, Struct Multidisc Optim, 50(6): 1175-1196, 2014, doi:10.1007/s00158-014-1107-x (download)
- TOP3D website: https://www.top3d.app/

Course Content

The main topics of this course are divided into three modules as follows:

Module I: Finite element analysis: Truss elements 1D, Truss elements 2D, Truss elements 3D, Q4 elements 2D, Brick elements 3D

Module II: Sequential convex approximations and sensitivity analysis: Mathematical form of a structural optimization problem, Weight minimization of truss structures, Finite element analysis methods for discrete and continuous structures, Convexity and KKT conditions, Lagrangian duality, Simultaneous and nested formulations, Numerical optimization methods, Sensitivity analysis

Module III: Topology optimization of distributed parameter systems and applications: Topology optimization of ground (truss) structures, Topology optimization of continuum structures (2D and 3D), Variable thickness sheet problem, Penalization, Applications.

The tentative topics by lecture and recommended readings are summarized below:

Lecture	Topic	Reading
L01	Introduction to topology optimization and Matlab	Opt: Ch. 1, FEA: Ch. 1
L02	FEA: Truss elements in 1D (springs)	FEA: Ch. 2, 3
L03	FEA: Truss elements in 2D	FEA: Ch. 4
L04	FEA: Truss elements in 3D; Mastan2	FEA: Ch. 5; Opt: Ch. 5
L05	Opt: Basics of convex programming Opt: Optimization of trusses structures `fmincon`	Opt: Ch. 4
	Exam 1: FEA: Ch. 1-5; Opt: Ch. 1-6	
L06	Opt: Convex approximation, SLP, SQP, CONLIN	Opt: Ch. 6
L07	Opt: MMA, Finite differences	Opt: Ch. 6
L08	Opt: Sensitivity analysis. KKT conditions (unconstr.)	Opt: Ch. 6
L09	Opt: KKT conditions (constr.)	Opt: Sec. 9.1.2
L10	Opt: Duality and the OC method.	Opt: Ch. 9
L11	FEA: Q4 elements and TO Matlab codes	FEA: Ch. 11
L12	Opt: Well-posedness, numerical problems, filters	Opt: Ch. 9
L13	Opt: Multi-load cases and compliant mechanisms	Papers
L14	Opt: Thermal problems. Passive and active regions	Papers
L15	Opt: Multimaterial TO	Papers
	Exam 2: FEA: Ch. 11; Opt: Ch. 9; Papers	

Course Policies

<u>Attendance</u>

The schedule shows the topics to be covered in each class meeting. You are expected to attend class prepared by studying the assigned material before the lecture. This allows for a more effective use of the class time. Note that the assigned material helps you establish some useful/relevant background on the subject but this doesn't necessarily mean that the exact same material will be covered during the lecture.

The progress of the independent research portion of the course will be assessed on weekly basis. The overall effectiveness of this research experience will be assessed based on students' reports. These reports will follow recommended practices in scientific writing. Their evaluation will be focused on the student's critical and independent thinking, intellectual depth, analysis rigor, quantitative skills, and the integration and application of engineering knowledge. Formative assessment (qualitative feedback) will be an integral part of the course. Research reports will be in a repository available to students taking this class in the future.

The learning experience will be assessed by the students through two course evaluations. A midterm student course evaluation will provide early feedback about the effectiveness of the course, while the final one, handled by the university, will also assess the relative effectiveness of this course in comparison to other ones.

<u>Methods of Assessment</u>

1. In-class exercises, homework and project problems will be used as the direct assessment method.
2. In-class discussions will be used as the indirect method for collecting students' feedback.
3. Students will be required to make a presentation to present the project, where their communication skills will be evaluated. A rubric for project evaluation is included in the syllabus.
4. Students are required to conduct a literature search in the project report. A rubric for project evaluation is included in the syllabus.
5. Formative and summative assessment: The multiple approaches to the different problems allow students to see the limitations of different techniques and approaches.
6. Criterion-referenced assessment: Final presentations of the projects will address a particular independent solution to each group of students that will differ from other groups.

<u>Description of Methods of Assessment</u>

1. In-class exercises and discussion during lectures to promote participation together with goal-oriented homework.
2. The student projects have different subjects but with the same general requirements regarding the length scale of the computational models. Using the rubric, the students are assessed on the complexity and completeness of the projects.

<u>Evaluation and grading criteria</u>

- In-class exercises will be submitted online. Only students who attended the class are allowed to submit.
- If you are unable to attend a class, you should let the instructor know in advanced. In special circumstances, the instructor may allow you to submit the in-class exercises.
- Homework will be submitted online. All homework must represent your own work. Consultation with other members of the class is allowed, but all work must represent an individual effort.
- Late submissions will not be accepted. Only properly submitted assignments will be graded.
- Neatness and a proper format are considered while grading.
- Exam problems will be of a difficulty level similar to that of homework problems. You are strongly advised to study the example solutions in the textbook/handouts and problems solved in class as well as work out additional problems from the textbook /handouts.
- The design project will be submitted online. A presentation will be required at the end of the course. The presentation may be peer-reviewed.

- Academic dishonesty is subject to punishment according to the relevant regulations. See: Cheating and plagiarism.

Grading and grading scale

Evaluation item	Percentage
In-class exercises (one per lecture)	25%
Homework (about one per week)	25%
First exam	25%
Second exam	25%
Total	**100%**

Grade	A+	A	A-	B+	B	B-	C+	C	C-	D+	D	D-
Minimum%	97	93	90	87	83	80	77	73	70	67	63	60

Cheating and plagiarism

Academic misconduct is subject to university punishment. Academic misconduct includes, but is not limited to, the following: 1) Cheating; 2) Fabrication; 3) Plagiarism; 4) Interference; 5) Violation of course rules; and 6) Facilitating Academic Dishonesty. Consequences for such actions and refer students to the section on "Academic Responsibilities and Misconduct" in the IUPUI Student Code of Conduct (Part II – G) at this website: http://www.iupui.edu/code/#P2_G
Students needed to check IUPUI Student Misconduct policy section of the IUPUI Student Code of Conduct (http://life.iupui.edu/dos/code.htm), if they are not already familiar with it.

American with Disabilities Act (ADA) compliance

If you need any special accommodations or assistance due to a disability, contact Adaptive Educational Services (AES) at (317)-274-3241. The office is located in Joseph T. Taylor Hall (UC), Room 100. AES website: http://aes.iupui.edu/services.html. No qualified individual with a disability shall, by reason of such disability, be either excluded from participation in or be denied the benefits of the services, programs, or activities" of Indiana University-Purdue University Indianapolis.

Additional help

During the semester, if you find that life stressors are interfering with your academic or personal success, consider contacting Counseling and Psychological Services (CAPS). All IUPUI students are eligible for counseling services at minimal fees. CAPS also performs evaluations for learning disorders and ADHD; fees are charged for testing. CAPS is located in UN418 and can be contacted by phone (317-274-2548). For more information, see the CAPS web-site at: http://life.iupui.edu/caps/