STRUCTURAL & MULTIDISCIPLINARY OPTIMIZATION

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COURSE OBJECTIVES

- To become familiar with optimization concepts in design and engineering processes.
- To be able to formulate your design problem as an optimization problem
- To present a systematic and critical overview of various numerical methods available to solve optimization problems.
- To be able to comment and analyze optimization results: convergence properties, meaning of solutions

COURSE OBJECTIVES

- The basic concepts are illustrated throughout the course by solving simple optimization problems. (Generally truss problems but can be extended to more general structural multidisciplinary problems)

- Several examples of application to real-life design problems are offered to demonstrate the high level of efficiency attained in modern numerical optimization methods.

- **Remark:** Although most examples are taken in the field of structural optimization, using finite element modeling and analysis, the same principles and methods can be easily applied to other design problems and simulation methods arising in various engineering disciplines: Mechanical, Electromagnetics, Fluid flows, Thermal, Chemical Engineering, etc.

OUTLINE

- INTRODUCTION TO OPTIMIZATION IN ENGINEERING
  - Engineering Design
  - Assumptions and definitions
  - Problem statement
  - Iterative optimization Process

- ELEMENTARY CONCEPTS IN STRUCTURAL OPTIMIZATION
  - Elementary problems from structural optimization:
    - Two bar truss
    - Three bar truss
    - Beam
    - Elliptical hole

OUTLINE

- INTRODUCTION TO MATHEMATICAL PROGRAMMING
  - Optimality conditions of single variable and multiple variable functions (KKT conditions)
  - Convex functions, convex sets

- PRIMAL AND DUAL PROBLEM STATEMENT
  - Lagrange function
  - Lagrangian problem

OUTLINE

- UNCONSTRAINED OPTIMIZATION
  - Descent methods for minimization
  - The method of steepest descent
  - Gradient Methods
  - Conjugate direction methods

- LINE SEARCH TECHNIQUES

- UNCONSTRAINED OPTIMIZATION
  - Newton methods
  - Newton-like,
  - Quasi Newton methods

- QUASI UNCONSTRAINED OPTIMIZATION

OUTLINE

- LINEARLY CONSTRAINED METHOD

- GENERAL CONSTRAINED OPTIMIZATION
  - Pure dual methods
    - Lagrange function
    - KKT conditions
    - Introduction to duality
    - Weak duality
    - Strong duality
    - Properties of dual function in Strong duality
    - Application to quadratic problems st linear constraints
    - Treatment of side constraints
    - Dual solutions of MMA subproblems

OUTLINE

- GENERAL CONSTRAINED OPTIMIZATION
  - Transformation methods: Barrier functions, Penalty function, Augmented Lagrangian methods
  - Direct (primal) methods
    - Gradient projection methods
    - Method of feasible directions
  - Linearization methods
    - Sequential Linear Programming SLP
    - Recursive Quadratic programming
    - Sequential Quadratic Programming SQP

OUTLINE

- STRUCTURAL OPTIMIZATION AND FINITE ELEMENT METHOD
  - Introduction to the Finite Element Method
    - Historical perspective
    - FEM of truss structures
    - FEM for linear elastic structures
  - Virtual Work Principal

- SENSITIVITY ANALYSIS
  - Linear static problems
  - Natural vibrations
  - Linear stability

OUTLINE

- OPTIMALITY CRITERIA
  - Principle of virtual work and Berke’s approximation of displacements
  - Fully stressed design
  - Minimum weight for a single displacement constraint
  - Extension to minimum weight subject to stress and displacement constraints

- GENERALIZED OPTIMALITY CRITERIA
  - The dual solution of OC with multiple constraints
  - The OC approximation as a first order approximation

OUTLINE

- STRUCTURAL APPROXIMATIONS
  - Linear approximation
  - Reciprocal approximations
  - Convex Linearization (CONLIN)
  - Method of Moving asymptotes (MMA)
  - Generalized Method of Moving Asymptotes
  - The MMA family schemes
  - Second order approximations
    - Diagonal SQP, GMMA…

OUTLINE

- SOLVING SEQUENTIAL CONVEX PROGRAMMING
  - Dual solvers
    - With convex and separable approximation
    - CONLIN and MMA
      - Subproblem formulation
      - Dual solvers for MMA and CONLIN

OUTLINE

- INTRODUCTION TO TOPOLOGY OPTIMIZATION
  - Optimal material distribution problem formulation
  - Microstructures and homogenization
  - Density filtering
  - Heaviside filtering
  - Sensitivity analysis
  - Compliance design
  - Strength design
  - Examples

OUTLINE

- SHAPE OPTIMIZATION
  - Representation of geometries
    - Parametric curves and surfaces
    - Constructive geometry
    - Level set description
  - Parametric approach of CAD systems
  - Sensitivity analysis wrt to boundary variables
    - Material derivatives
    - Velocity field concept
    - Velocity field calculation
  - Extension to XFEM and Level set description
  - Industrial software tools
  - Examples

OUTLINE

- COMPOSITE STRUCTURE OPTIMIZATION
  - Parameterization of composites
  - Problem formulation
  - Sensitivity analysis
  - Solution aspects

- META HEURISTIC ALGORITHMS
  - Introduction to meta heuristic optimization algorithms
  - Genetic Algorithms
  - Simulated Annealing
  - Particle Swarm Optimization

Project 1: Unconstrained Minimization

- Solve optimization unconstrained minimization problems using computer and MATLAB to experiment the optimization methods presented during the lectures

- Build up your MATLAB code to solve:
  - Unconstrained minimization of quadratic and non quadratic functions
  - Comment convergence properties
  - Analyze the results

- Evaluation:
  - Individual computer work
  - Report and Power Point presentation (max 20 pages)
  - MATLAB code
  - Deadline: November 11, 2020 (12:00 AM)

Project 2: Optimality criteria and duality

- Write your optimality criteria code to solve truss problems

- Goal: solve efficiently your topology optimization problem
  - Solve analytically a truss optimization problem using OC
  - Write your MATLAB code to solve truss structures using bar FEM
  - Implement OC to solve truss mass minimization

- Evaluation:
  - Individual analytical and computer work
  - Report and Power Point Presentation (max 20 pages)
  - Deadline December 4, 2020 (12:00 AM)

Project 3: Topology optimization with MATLAB

- Building up your own topology optimization solver to experiment with topology optimization

- Goal: solve efficiently your topology optimization problem
  - Write your MATLAB code to experiment for TO parameters
  - Ref: A 99-line topology optimization code written in Matlab. O. Sigmund. Struct. Multidisc. Optim. 21, 120–127
  - Available at www.topopt.dtu.dk/

- Evaluation:
  - Individual computer work
  - Report and Power Point Presentation (max 20 pages)
  - Deadline January 4, 2021 (12:00 AM)

LECTURES

- Green code:
  - Course are given in presence.
  - No constraint

- Yellow code (now)
  - Half of seats are occupied. Min distance 1,0 m. (Preferably 1,5m). Masks are mandatory.
  - Classroom is divided into two groups because no other room is available.
  - Professor do swap after each week (cycles of two weeks)
  - Podcast are recorded during the lectures and posted on MyUliege platform
  - Students are allowed on the campus, but presence must be reduced

LECTURES

- Orange code
  - Max 20% of the students on the campus
  - Course given remotely
  - Podcast are recorded before or delivered using Balckborad Collaborate.
  - Discussion sessions are organized either in small groups or via visio conference systems (LIFESIZE)

- Red code
  - Students are forbidden on the Campus
  - All lectures are recorded and delivered via podcast are recorded during the lectures and posted on MyUliege platform
  - Discussion sessions are organized are only allowed using visio conference systems (LIFESIZE)

AGENDA

Date	Time	Group A (1/94 Montefiore)	Group B (1/126 Montefiore) EMSHIP
15/09	13:45	General Introduction (P. Tossings)	General Introduction (P. Duysinx)
	14:30	Introduction to Math Programming including KKT (P. Tossings)	Introduction to Optimization in Engineering (P. Duysinx)
22/09	13:45	Introduction to Optimization in Engineering (P. Duysinx)	Introduction to Math Programming including KKT (P. Tossings)
29/09	13:45	Unconstrained optimization: Gradient methods. Adaptation to quasi unconstrained problems (P. Tossings)	Elementary Concepts in Structural Optimization. Test problems. (P. Duysinx)
	15:45		Finite Elements Methods and Optimization (P. Duysinx)
06/10	13:45	Elementary Concepts in Structural Optimization. Test problems. (P. Duysinx)	Unconstrained optimization: Gradient methods. Adaptation to quasi unconstrained problems (P. Tossings)
13/10	13:45	Line Search Techniques (P. Tossings)	Optimality Criteria (P. Duysinx)
	15:45	Project 1: Unconstrained Minimization	Project 1: Unconstrained Minimization
		Introduction to MATLAB	Introduction to MATLAB

AGENDA

Date	Time	Group A (1/94 Montefiore)	Group B (1/126 Montefiore) EMSHIP
20/10	13:45	Optimality Criteria (P. Duysinx)	Line Search Techniques (P. Tossings)
	15:45	Supervised work	Supervised work
		Project 2: Truss optimization using OC	Project 2: Truss optimization using OC
27/10	13:45	Unconstrained optimization: Newton, Newton-like, quasi-Newton. (P. Tossings)	Generalized OC: from OC to Sequential Convex Programming (P. Duysinx)
	15:45	Supervised work	Supervised work
03/11		AUTOMN BREAK	
10/11	13:45	Generalized OC: from OC to Sequential Convex Programming (P. Duysinx)	Unconstrained optimization: Newton, Newton-like, quasi-Newton. (P. Tossings)
	15:45	Supervised work	Supervised work

AGENDA

Date	Time	Group A (1/94 Montefiore)	Group B (1/126 Montefiore) EMSHIP
17/11	13:45	General Constrained Optimization. Duality. (P. Tossings)	Introduction to topology optimization (P. Duysinx)
	15:45		Supervised work
	23:59	Deadline Project 1	Deadline Project 1
24/11	13:45	Introduction to topology optimization (P. Duysinx)	General Constrained Optimization. Duality. (P. Tossings)
	15:45	Project 3: Topology optimization	Project 3: Topology optimization
		Supervised work	
01/12	13:45	General Constrained Optimization: transformation methods. (P. Tossings)	Sensitivity analysis (P. Duysinx)
	15:45	Supervised work	Supervised work
04/12	23:59	Deadline Project 2	Deadline Project 2

AGENDA

Date	Time	Group A (1/94 Montefiore)	Group B (1/126 Montefiore) EMSHIP
08/12	13:45	Sensitivity analysis (P. Duysinx)	General Constrained Optimization: transformation methods. (P. Tossings)
	15:45	Supervised work	Supervised work
15/12	13:45	Introduction to Shape Optimization (P. Duysinx)	Supervised work Q&A bout the course
	15:45	Supervised work Q&A about the course	Introduction to Shape Optimization (P. Duysinx)
19/12		WINTER BREAK	
03/01	23:59	Deadline Project 3	Deadline Project 3
**/01		EXAM	EXAM

EXAMS AND ASSESSMENT

- Oral exam: theory (60%)
  - Two questions of theory
  - Questions about computer projects
  - In January
  - Organized in presence or via visio conference (wait and see)

- Computer projects (40%)
  - Reports & Program
  - Discussion during oral exam
  - Students must attend at least 60% of the supervised computer work sessions to defend.

LECTURE NOTES

- E-Campus platform
  - Copy of slides
  - Copy of Lectures (available later)
  - Discussion Forum

- MyUliege
  - Podcast (if available)

- Copy of the slides
  - Lecture slides by Pierre Duysinx
  - Web site: www.ingveh.ulg.be > cours > MECA0027

REFERENCES

- Highly recommended
  - P.W. Christensen & A. Klarbring. An introduction to structural optimization. Springer. 2010.

- Optional
  - Programmation mathématique : théorie et algorithmes (Tome 1). M.Minoux. Dunod, Paris, 1983.
  - Foundations of Structural Optimization: A Unified Approach. A.J. Morris. John Wiley & Sons Ltd, 1982
  - Haftka, R.T. and Gürdal, Z., Elements of Structural Optimization, 3rd edition , Springer, 1992
  - Topology Optimization, Theory, Methods, and Applications. M.P. Bendsoe and O. Sigmund, Springer Verlag, Berlin, 2003.

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