DESIGNING WITH TOPOLOGY OPTIMIZATION

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LAY-OUT

- Introduction
- Design process loop
- Design methodology using topology optimization
- Numerical applications
- Conclusion
MOTIVATION
MOTIVATION

- Morphology of component has a great influence on the final performance

- Unappropriated choice of topology can limit the final satisfaction of the specifications

- Engineers used to trust in their intuition or former knowledge of the topic and empirical choices

- Need for new methods to replace empirical choice or trial-and-error process $\rightarrow$ topology optimization

- Topology optimized components can reach gains of 50 to 100% in terms of overall performance
MOTIVATION

- CAD approach does not allow topology modifications

A better morphology by topology optimization (Duysinx, 1996)
PLACE OF TOPOLOGY OPTIMIZATION IN THE DIGITAL DESIGN CHAIN
A PRELIMINARY DESIGN TOOL

- Topology optimization is a preliminary design tool that must be followed by additional steps of design and verifications.

- Topology optimized results must be post treated:
  - Optimized results are not black-and-white pictures. They include intermediate density regions or microstructures. Microstructures cannot be manufactured using classic manufacturing processes.
  - Topology optimization considers only a subset of design specifications. Additional simulations.
  - Simulation and fabrication often require smooth boundary contours: interpretation and reconstruction of a parametric CAD model.
Continuous design chain
- Topology optimization has to determine a good morphology
  - Global criteria
  - Boundary conditions
  - Linear analysis?
- Shape and sizing optimizations has to refine the design to cope with the full specification booklet
  - Local constraints
  - Non linear simulation
  - Manufacturing...
INTEGRATION OF SHAPE AND TOPOLOGY

- Shape of design domain can change topology and vice-versa
- Non-continuous mapping between optimized topology and design domain shape (Bruyneel)
- Interlaced shape and topology optimization processes (Maute & Ramm, 1994)
- Simultaneous shape and topology optimization (Kuci, 2018)
METHODOLOGY FOR TOPOLOGY OPTIMIZATION PROJECT
METHODOLOGY

- Carrying out successfully a topology optimization process requires a structured methodology
- Accounting correctly for the problems specifications:
  - Boundary conditions
  - Load cases
  - Symmetry conditions
  - Problem formulation
- Selecting appropriated TO process parameters:
  - Power penalization,
  - Volume constraints,
  - Filter parameters: density and thresholding functions
  - Material interpolation laws
  - Finite element discretization
- Optimization algorithms
METHODOLOGY

1/ Choice of the design domain

- Can be used to prescribe overall design constraints (packaging, system integration)
- Be careful with infinite boundary conditions: avoid interaction of the optimized material distribution with the design domain boundaries
- Be able to account for the fixations, loads, etc.
- Take benefit of symmetry conditions, repeated patterns, etc.
METHODOLOGY

- Choice of the design domain
METHODOLOGY

- Choosing the appropriated loads and boundary condition is essential!
METHODOLOGY

- Large design domain gives full freedom to the designer
- Design domain can restrain the optimized distribution
METHODOLOGY

- No symmetry
  - No geometrical symmetry
  - No loading symmetry

- Symmetry about y-axis
  - Use structural frame (.FRAME)
  - Applicable on non symmetric meshes
  - Applied only on optimizable design elements

- Symmetry about x-axis
METHODOLOGY

- No symmetry
  - No geometrical symmetry
  - No loading symmetry

- With 60° cyclic symmetry

- With mirror symmetry inside sector
METHODOLOGY

2/ Identification of design variables

- Non design parts
  - Part with full density material (mandatory presence of material)
    - Loads application points
    - Supports
    - Functional surfaces for connections
  - Parts with zero density ➔ holes or other components
METHODOLOGY

- Select groups of elements
- TOPOLVAR ➔ optimizable elements
- TOPOLFIX ➔ fixed density element = removed from optimization
- But default: all elements are optimized

Define the cylinders holes as non design
METHODOLOGY

- Non design regions
METHODOLOGY

- 3/ Choice of a material interpolation law / composite microstructure

- Interpolation is necessary to relax the 0/1 optimization problem → continuous variable optimization

- Penalization: reduce intermediate density regions

- Optimal microstructures like rank-N materials → full mathematical relaxation

- Other microstructures or mathematical interpolation laws: Uncomplete relaxation
METHODOLOGY

☐ 3/ Choice of a material interpolation law / composite microstructure

☐ SIMP (Simply Isotropic Material with Penalization):

\[ E(x) = x^p E^0 \quad p > 1 \]

☐ Modified SIMP should be preferred to avoid singularities

\[ E(x) = E_{min} + x^p (E^0 - E_{min}) \]

☐ Choice of parameter p
  - Classic choice \( p = 3 \! \! \! \! \) 
  - Low penalization (very stable convergence) \( p = 1.6 \)
  - High penalization (but many local optima!) \( p = 4 \) or more...
METHODOLOGY

SIMP with $p=2$

SIMP with $p=3$

SIMP with $p=4$
3/ Choice of a material interpolation law / composite microstructure

- Alternatively RAMP parameterization (Stolpe & Svanberg, 2001) enables controlling the slope at zero density

\[ E(x) = \frac{x}{1 + p(1 - x)} E^0 \]

- Halpin Tsai (1969)

\[ E(x) = \frac{r x}{(1 + r) - x} E^0 \]

- Polynomial penalization (Zhu, 2009):

\[ E(x) = \left( \frac{\alpha - 1}{\alpha} x^p + \frac{1}{\alpha} x \right) E^0 \]

- Necessary for problems like self-weight, eigenvalue problems (vibration, stability)!
4/ Finite element model

- Mesh with appropriate density
  - Free mesh is possible
  - Mesh regularity: quadrangular finite element should be preferred
METHODOLOGY

4/ Finite element model

- Finite element type and approximation
  - Assumption: plate elements, volume elements, bending elements
  - Approximation degree: degree 2 is better for checkerboard alleviation and stress estimation but the CPU cost is very expensive
  - Degree 1 is possible but should be completed by density filter or perimeter constraint

- Discretization of the density field
  - Most usual discretization: constant density per finite element (centroid density)
  - Node discretization and linear interpolation function is possible
  - Level set discretization or phase field are alternative options
METHODOLOGY

4/ Finite element model

- Initial density distribution
  - Uniform average density
  - Random density distribution with average satisfying volume constraint
  - Full material density
METHODOLOGY

- Meshing the design domain
Irregular meshes give poor results
METHODOLOGY

- Irregular meshes give poor results

FE Degree 1

FE Degree 2

FE triangular Degree 2
5/ Regularization strategy
  – Mesh independency
  – Checkerboard alleviation
  – Minimum size
  – Perimeter method: not popular anymore

  Three field method
    – Density filtering
    – Heaviside filtering
Two numerical difficulties

- **Checkerboard patterns**: numerical instabilities related to the inconsistency between the displacement and density fields.
  - Appearance of alternate black-white patterns
  - Checkerboard patterns replaces intermediate densities

- **Mesh dependency**: the solution depends on the computing mesh.
  - New members appears when refining the mesh
  - Number of holes and structural features is modified when changing the mesh.
  - Stability (and meaning) of solutions?
THE THREE FIELD APPROACH

- Three field topology optimization scheme proposed by Wang et al. (2011),
  - Density filtering
    \[ \tilde{x}_e = \frac{\sum_{i \in N_e} w_i(X) v_i x_i}{\sum_i w_i(X_i) v_i} \]
  - Heaviside filter
    - Thresholding
    - Erode / delate geometry
      \[ \hat{x}_e = \frac{\tanh(\beta \mu) + \tanh(\beta (\tilde{x}_e - \mu))}{\tanh(\beta \mu) + \tanh(\beta (1.0 - \mu))} \]
METHODOLOGY

- Filter size must be:
  - Sufficiently large
  - Independent of the mesh size (absolute dimension)

- In NX, standard size of the filter
  - 2D ➔ 8 elements
  - 3D ➔ 16 elements
7/ Optimization of the density distribution

- One iteration includes:
  - One FE analysis
  - Sensitivity analysis
  - Optimization using CONLIN or MMA
  - Update the density field

- Define the problem characteristics
  - Add/edit specific data
    - Formulation:
    - Optimization control
    - Topology optimization control:
  - Manage execution
  - Drive post-processing action
METHODOLOGY

- Define the problem characteristics
  - Add/edit specific data
  - Manage execution
  - Drive post-processing action
METHODOLOGY

- Minimize compliance
  s.t.
  - Given volume
  - (bounded perimeter)
  - (other constraints)

- Maximize eigenfrequencies
  s.r.
  - Given volume
  - (bounded perimeter)
  - (other constraints)

- Minimize the maximum of the local failure criteria
  s.t.
  - Given volume
  - (bounded perimeter)
  - (other constraints)
METHODOLOGY

- **Volume constraint:**
  - Typically between 20 to 80 $\rightarrow$ average value: 50%
  - If mass constraint is given: naturally prescribed!
  - If no mass constraint: volume is a design parameter
    - In the mean range $[30\%; 70\%]$, it has not generally a major influence on final topology but more a sizing influence.
  - Convergence becomes very delicate for very low density constraint i.e. $V_{\text{max}} < 15\%$ design domain volume
METHODOLOGY

Volume = 40%

Volume = 20%

Volume = 60%
METHODOLOGY

- **Optimization algorithm**
  - Best algorithms used dual maximization and convex approximations
    - CONLIN \(\rightarrow\) SPOT
    - MMA
    - GCMMA in case of non monotonic responses (e.g. self weight)
  - Convergence must be understood in terms of design variable stationarity NOT in terms of objective function!
    - Stopping criteria is the modification of the design variables
    - Not picture nice looking stopping criteria
  - Topology optimization convergence requires at least 100 iterations but more generally 250 iterations
METHODOLOGY

- **Optimization algorithm**
  - If starting from infeasible design, the first iterations are devoted to find a first feasible design point (generally satisfying the volume constraint)
  - When convergence is unstable, resort to tight move-limits

\[
\hat{x}_i - \alpha_i \leq x_i \leq \hat{x}_i + \beta_i
\]

- Typically

\[
\alpha_i = \beta_i = \Delta x_i = 0, 3
\]
METHODOLOGY

8/ Visualization and interpretation of optimized density map
   - Visualization of density maps
   - Interpret optimized density
   - Construct a smooth Computer Aided Design (CAD) model
     - Introduce aesthetic or manufacturing constraints if necessary
METHODOLOGY

- Interpret the optimized topology

- Define the nature of structural members:
  - Beams
  - Plates
  - Volume
METHODOLOGY

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METHODOLOGY

- 2D CAD model reconstruction

![2D CAD model reconstruction](image1)

- Manual reconstruction

![Manual reconstruction](image2)

- Automatic curve fitting

![Automatic curve fitting](image3)
METHODOLOGY

- 2D CAD model reconstruction

- Two zones:
  - Frame structure
  - Shear panel
METHODOLOGY

- Interpreting the optimized density distribution
METHODOLOGY

- Interpreting the optimized density distribution
METHODOLOGY

- Smoothing density distribution with NX10
NUMERICAL APPLICATIONS
SHAPE & TOPOLOGY OPTIMIZATION OF MAG’IMPACT EJECTOR

padding

BC: clamping
TOPOLOGY OPTIMIZATION OF EJECTOR

- Topology optimization with optimized bolt positions
  - Mesh and design domain

![Mesh and design domain](image)

- Material distribution field

![Material distribution field](image)

5627 FE
3524 density var.

Mass=49.7 kg
(-27%)
Compliance: 0.35J
(-50%)
TOPOLOGY OPTIMIZATION OF EJECTOR

- Topology optimization of reference configuration
  - Mesh and design domain

- Material distribution field

3655 FE
2578 density var.

Mass=59.3 kg
Compliance: -9%
TOPOLOGY OPTIMIZATION OF EJECTOR

- Topology optimization of reference configuration
  - Material distribution field

- Stress field

Mass = 59.3 kg

\( \sigma_{\text{max}} = 21.6 \text{ MPa} \)
TOPOLOGY OPTIMIZATION OF EJECTOR

- Topology optimization with optimized bolt positions
  - Mesh and design domain

- Material distribution field

Mass=49.7 kg (-27%)
Compliance: 0.35J (-50%)
TOPOLOGY OPTIMIZATION OF EJECTOR

- Topology optimization of reference configuration
  - Material distribution field

Mass = 49.7 kg

\[ \sigma_{\text{max}} = 17.8 \text{ MPa} \]

- Stress field
TOPOLOGY OPTIMIZATION OF EJECTOR

- Effect of counter-weight design?

- Sensitivity of compliance (finite difference)
TOPOLOGY OPTIMIZATION OF EJECTOR

- Topology optimization with optimized 2 bolt positions

6007 FE - 3886 density var.

- Material distribution field (it=200)

Compliance = 0.47J - Mass = 51.5 kg

$\sigma_{\text{max}} = 25.5$ MPa
3D TOPOLOGY OPTIMIZATION OF EJECTOR

- Topology optimization: 3D model
  - FE: 135 000
  - Design variables: 107 000

- Mass: 58.7 kg
- Compliance: 1.35 J

- Boundary conditions:
  - 1/ bolt holes clamped
  - 2/ bold hole 1 clamped and wall boxes of holes 2 and 3 clamped
3D TOPOLOGY OPTIMIZATION OF EJECTOR

- Topology optimization using BC1

Topology similar to 2 results

Mass = 47.7 kg
Compliance = 0.52 J (-62%)

Wall box have disappeared
TOPOLOGY OPTIMIZATION OF EJECTOR

- Mostly 2D problem here: geometry remains nearly extruded from 2D
- Other boundary conditions can modify the geometry
- Worn geometry is not a critical load case
3D TOPOLOGY OPTIMIZATION OF EJECTOR

- Topology optimization using set of BC 2

Topologies of wall box and bolt bores are different

Mass = 43kg
Compliance = 0.62J (-55%)
3D TOPOLOGY OPTIMIZATION OF EJECTOR

- Topology optimization based on used geometry
  
  FE: 135 000  
  Design variables: 73 131

- Set of BC 2 only

  Mass: 49 kg  
  Compliance: 0,85J
3D TOPOLOGY OPTIMIZATION OF EJECTOR

- Topology optimization using used geometry

Topologies of wall box and bolt bores are different

Mass = 32.4 kg
Compliance = 0.33 J (-55%)
INTERPRETATION OF OPTIMIZED EJECTOR

- Shape description using Level Sets