Topological Optimization for AM
Contribution to design of support structures
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Topological Optimization

Principles

• Part of the design process of a shape
• Find a shape $\Omega$ which minimizes an objective $F$ with respect to the constraints $G_i$

$$\begin{cases} \min_{\Omega \subset D} F(\Omega) \\ \forall i, G_i(\Omega) \leq G_{max}^i \end{cases}$$

• Examples of objective: volume, mass
• Examples of constraint: eigenfrequencies, displacement of a node, thermal flux

• Iterative method: we start from an initial shape $\Omega_0$ that we improve step-by-step
Topological Optimization
Shape representation on fixed mesh

• Design Space is meshed once and never modified during optimization

• Shape represented with a Level-Set, the signed distance to boundary
  - $\psi(x) < 0$ if inside the shape
  - $\psi(x) > 0$ if outside the shape
  $\Rightarrow \psi(x) = 0$ the boundary of the shape

• Precise knowledge of the location of the boundary on a non-fitting mesh

Engine support Courtesy Renault
Topological Optimization

Key features of TOPAZE

• Physic engines
  • Static (linear or non-linear)
  • Eigenmode computation
  • Harmonic response (direct or modal)
  • Thermal

• Criteria
  • Volume, surface, perimeter
  • Mass, thickness
  • Molding, symmetry
  • Displacement, velocity, acceleration, temperature
  • Stress, strain, heat flux

• Fully integrated Into Visual-Environment
  • More info https://myesi.esi-group.com/products/multiphysics
Example: Engine Bracket

Geometry and mechanics

- System units: mm, t, sec, K
- Material: Titan alloy Ti-6Al-4V
  - Young’s Modulus = 114000 MPa
  - Poisson’s ratio = 0.342
  - Density = 4.2e-9 t/mm3
  - Thermal conductivity 7.2 W/m/K
- 3 subcases
  - Static Mechanical analysis
    - 4 load cases
  - Eigen Frequency
    - Free-free 10 modes
  - Static Thermal analysis
    - 1 load case
Example: Engine Bracket
Performance specifications

- On subcase 1:
  - Volume reduction
  - Displacement norm Node 22746 LC1 < 0.7 mm
  - Displacement norm Node 22746 LC2 < 0.8 mm
  - Displacement norm Node 22746 LC3 < 0.5 mm
  - Displacement norm Node 22747 LC4 < 0.06 mm
  - Max across E_OPTIMIZED of Von Mises Stress LC1 - LC4 < 1000 MPa

- On subcase 2:
  - First physical Eigenfrequency (MODE 7) > 3850 Hz

- On subcase 3:
  - Max across CONTROL_AREA of Temperature < 480°K
Example: Engine Bracket

Results
Example: Engine Bracket
The remeshed optimal shape

- At the end of an optimization, TOPAZE remeshes the optimal shape
Application to Additive Manufacturing

Support structures

• The aim is to minimize the thermo-mechanical effects of overhangs

• Collaboration with Grégoire Allaire and Beniamin Bogosel, CMAP, Polytechnique School
  • Support optimization in additive manufacturing for geometric and thermo-mechanical constraints”, Allaire G, Bihr M, and Bogosel, B, to be submitted

• Part of SOFIA project (SOLution pour la Fabrication Industrielle Additive métallique), [https://www.sofia-3d.fr/](https://www.sofia-3d.fr/)
Application to Additive Manufacturing

Support structures: Mechanical

• First step is minimizing the mechanical effects of overhangs, without taking into account a thermal model
  • Thermo-mechanical is a bit more complex

• We suppose that the shape is already designed

• We only optimize the supports
  • The model is submitted to the gravity
  • Objective: minimize volume of the supports
  • Constraint: compliance of the (shape+supports) has a maximum
Application to Additive Manufacturing
Support structures: examples

Pictures courtesy of Beniamin Bogosel, CMAP, Polytechnique School
Application to Additive Manufacturing
Support structures: examples

Pictures courtesy of Beniamin Bogosel, CMAP, Polytechnique School
Application to Additive Manufacturing
Support structures: Thermal evacuation

• We suppose that the shape is already designed

• We optimize the supports to maximize the thermal evacuation:
  • The model is submitted to a constant thermal source in the shape
  • One of the side of the model is “cold” (T=0)
  • Objective: minimize thermal compliance of (shape + supports)
  • Constraint: volume of supports is bounded
Application to Additive Manufacturing

Support structures: examples

Pictures courtesy of Beniamin Bogosel, CMAP, Polytechnique School
Application to Additive Manufacturing
Support structures with forbidden areas

• We suppose that the shape is already designed.

• We optimize the support structures (for thermic or static problem), but they can’t lean on unattainable areas
  • Geometrical criterion:
    • We compute the “access range” of each areas
    • Penalization of the volume of support outside these “access ranges”

• Special treatment of the level-set on these areas
Application to Additive Manufacturing
Support structures: example

U-shaped Tube without forbidden areas

Pictures courtesy of Beniamin Bogosel, CMAP, Polytechnique School
Application to Additive Manufacturing
Support structures: example

U-shaped Tube with forbidden areas

Pictures courtesy of Beniamin Bogosel, CMAP, Polytechnique School
Conclusions

• **TOPAZE** allows users to solve problems of topological optimization
  • It is based on the Level-Set technology, which guaranties an exact definition of the optimal shape

• For the 2020 version, as part of the SOFIA project, we plan to integrate tools for supports
  • Mechanical optimization
  • Thermal optimization
  • Forbid some areas

• More developments are in progress
  • Full thermo-mechanical optimizations
  • Optimization of the supports taking into account the slice-by-slice process of AM
  • Synergy **ESI-AM, our solutions for Metal Additive Manufacturing**
Thank you
Topological Optimization

Shape representation with a Level-Set

- Simple scalar function $\psi$ to define the shape
- Conventionally: the signed distance to boundary
  - $\psi(x) < 0$ if inside the shape
  - $\psi(x) > 0$ if outside the shape
  - $\Rightarrow \psi(x) = 0$ the boundary of the shape
- Precise knowledge of the location of the boundary on a non-fitting mesh
- Evolution of the shape using a descent direction $\nu$, computed from objective and constraints.
  - Hamilton-Jacobi equation $\frac{\partial \psi}{\partial t} + \nu \| \nabla \psi \| = 0$
Geometrical Constraints

Maximum Thickness

• Criterion that leads to topological changes depending on the threshold
• The optimizer changes the number of bars to fit the constraint

No $e$

$e = 0.4$

$e = 0.2$
Semi Infinite Constraints

Maximum Von Mises example

- L-shape optimization
  - A fillet is needed to reduce stress
Manufacturing Constraints

Molding

• Criterion that leads to topological changes depending on the molding direction and parting surface definition
• The parting surface can also be unknown

No molding

Molding in Z direction with parting surface Z=0

Molding in Y direction with parting surface Y=0.5

Molding in Z direction without parting surface