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Survey

A survey of manufacturing oriented topology optimization methods

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ABSTRACT

Topology optimization is developing rapidly in all kinds of directions; and increasingly more extensions are oriented towards manufacturability of the optimized designs. Therefore, this survey of manufacturing oriented topology optimization methods is intended to provide useful insight classification and expert comments for the community.

First, the traditional manufacturing methods of machining and injection molding/casting are reviewed, because the majority of engineering parts are manufactured through these methods and complex design requirements are associated. Next, the challenges and opportunities related to the emerging additive manufacturing (AM) are highlighted. SIMP (Solid Isotropic Material with Penalization) and level set are the concerned topology optimization methods because the majority of manufacturing oriented extensions have been made based on these two methods.

1. Introduction

In the past two decades, topology optimization has become an active research field and the related algorithms developed create a powerful approach to perform innovative and efficient conceptual design activities [148]. To be specific, topology optimization is powerful because the related algorithms have been applied to a broad range of design problems governed by different physical disciplines, i.e. solid mechanics [1,8,121,134], fluid dynamics [9,151], and thermal dynamics [43,135,154] etc. Many algorithms developed are innovative because they can help engineers to think out of the box to generate innovative design ideas, even for those designs of already highly engineered products [148]. Furthermore, topology optimization is efficient because automated optimization processes are employed to generate the conceptual designs instead of the conventional trial-and-error approach.

Currently, SIMP (Solid Isotropic Material with Penalization) [8], ESO (Evolutionary Structural Optimization) [134], and level set [1,86,121] topology optimization methods represent the main streams. These methods have their unique characteristics and at the same time, are tightly associated. There have been a few comprehensive reviews in the literature [26,28,89,98,99,112,117].

ESO is categorized as a hard-kill method which iteratively removes or adds a finite amount of material. Heuristic criteria are employed which may or may not be based on the stringently calculated sensitivity information. Therefore, ESO is relatively simple in implementation which demonstrates advantages for topology optimization problems involving complex physical processes. For instance, Naceur et al. [90] designed the initial blank through ESO which involved finite element analysis of the sheet metal forming process. Azamirad and Arezoo [6] optimized the stamping die through ESO which performed numerical simulation of the sheet metal forming process through Abaqus. Shao et al. [104,105] optimized forging preforms though ESO and the forging process was simulated through the DEFORM 2D. However, as summarized in [89], there is almost no implementation of the ESO method to address other manufacturing oriented topology optimization problems. Therefore, this survey paper pays more attention to SIMP and level set methods, because the majority of manufacturing oriented extensions have been so far developed based on these two methods.

The typical compliance minimization problem based on SIMP method is demonstrated (see [8] for more details) in Eq. (1).

$$
\begin{aligned}
& min.\, C = \boldsymbol{U}^T \boldsymbol{K}\boldsymbol{U} = \sum_{e=1}^{n} \boldsymbol{u}^e \boldsymbol{k}^e \boldsymbol{u}^e = \sum_{e=1}^{n} (\rho^e)^p \boldsymbol{u}^e \boldsymbol{k}_0 \boldsymbol{u}^e \\
& s.t.\, V = \sum_{e=1}^{n} \rho^e v_0 \le V_{max} \qquad (1) \\
& \boldsymbol{K}\boldsymbol{U} = \boldsymbol{F} \\
& 0 < \rho_{min} \le \rho^e \le 1
\end{aligned}
$$

where $\boldsymbol{U}$ and $\boldsymbol{F}$ are the global displacement vector and loading vector, respectively. $\boldsymbol{K}$ is the global stiffness tensor. $\boldsymbol{u}^e$ is the element displacement vector and $\boldsymbol{k}^e$ is the element stiffness tensor after density interpolation. $\boldsymbol{k}_0$ and v_0 are the stiffness tensor and

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material volume of a solid element, respectively. ρ^e is the element density and ρ_{min} is the lower bound. V_{max} is the upper bound of the in total material volume.

It is worth noting that, compared to direct density optimization, interpolation of the nodal or point-wise densities with material properties is also an effective approach [36,56,81] which has contributed to achieving the manufacturing-oriented topology design, such as minimum length scale control for machining and bi-directional material change for injection molding/casting. More details will be discussed in later sections.

Comparatively, the typical problem formulation based on level set method is demonstrated in Eq. (2).

$$
\begin{aligned}
&\min \quad C = \int_D \boldsymbol{Ae}(\boldsymbol{u})\boldsymbol{e}(\boldsymbol{u})H(\Phi)d\Omega \\
&s.t. \;\; a(\boldsymbol{u}, \boldsymbol{v}, \Phi) = l(\boldsymbol{v}, \Phi), \quad \forall \boldsymbol{v} \in U \\
&V = \int_D H(\Phi)d\Omega \le V_{max} \\
&a(\boldsymbol{u}, \boldsymbol{v}, \Phi) = \int_D \boldsymbol{Ae}(\boldsymbol{u})\boldsymbol{e}(\boldsymbol{v})H(\Phi)d\Omega \\
&l(\boldsymbol{v}, \Phi) = \int_D \boldsymbol{pv}H(\Phi)d\Omega + \int_D \boldsymbol{\tau v}\delta(\Phi)|\nabla\Phi|d\Omega
\end{aligned}
\tag{2}
$$

in which $\boldsymbol{u}$ is the displacement vector, $\boldsymbol{v}$ is the test vector, and $\boldsymbol{e}(\boldsymbol{u})$ is the strain. $U = \{\boldsymbol{v} \in H^1(\Omega)^d | \boldsymbol{v} = 0 \ on \ \Gamma_D\}$ is the space of kinematically admissible displacement field. $\boldsymbol{A}$ is the Hooke's law for the defined isotropic material. $\boldsymbol{p}$ is the body force and $\boldsymbol{\tau}$ is the boundary traction force. Φ is the level set function, which is defined by Eq. (3).

$$
\begin{cases}
\Phi(\boldsymbol{X}) > 0 & \forall \boldsymbol{X} \in \Omega \quad (material) \\
\Phi(\boldsymbol{X}) = 0 & \forall \boldsymbol{X} \in \Gamma \quad (interface) \\
\Phi(\boldsymbol{X}) < 0 & \forall \boldsymbol{X} \in D \backslash \Omega \quad (void)
\end{cases}
\tag{3}
$$

The adopted Heaviside function H and the Dirac Delta function δ are defined in Eq. (4) and Eq. (5), respectively.

$$
\begin{cases}
H(\Phi) = 0 & \Phi < 0 \\
H(\Phi) = 1 & \Phi \ge 0
\end{cases}
\tag{4}
$$

$$
\begin{cases}
\delta(\Phi) = 0 & \Phi \ne 0 \\
\delta(\Phi) = +\infty & \Phi = 0
\end{cases}
\qquad \int_{-\infty}^{+\infty} \delta(\Phi)d\Phi = 1
\tag{5}
$$

By comparing Eqs. (1) and (2), the distinctions between SIMP and level set can be observed. SIMP method employs the element or nodal densities as the optimization variables, which is referred to an element based method. It can freely generate topology changes and have fast and stable convergence; however, the derived structural boundary tends to be blurred and staggered. Level set method defines the material domain by the positive level set field and the structural boundary by the zero-value level set contour, which is categorized as a boundary based method. However, because of the boundary based structural evolution, the employed shape derivative generally only leads to shape deformations if no interior void exists inside the design domain, and topology changes are usually forced by predefining interior holes or applying topological derivative.

On the other hand, as revealed by other authors [112], the distinctions between the two methods are in fact not that fundamental. It is typically claimed that level set method employs clear-cut and smooth boundary representation, but in most implementations, the boundary elements are modeled through the approximate Heaviside projection and what passed into the finite element model is actually blurred. In addition, density field projection is quite commonly applied these days [36,110] which makes it similar to the Heaviside projection of the level set function. As mentioned in [112], hybrid application of these two methods may be a trend of future research which could benefit from the advantages of both methods.

From the perspective of software implementation, topology optimization has been embedded as a module of most commercial CAD/CAE systems, e.g. the OptiStruct [4] from Altair HyperWorks, and the SIMULIA Tosca Structure [25] applied in Abaqus, ANSYS, and MSC Nastran. Additionally, some advanced toolkits have been released by academic research groups, e.g. the TopOpt (http://www.topopt.dtu.dk) from TopOpt research group and the PareTOWorks (http://www.ersl.wisc.edu) from Engineering Representations and Simulation Laboratory, etc. Other than that, several Matlab programs can be found in academic publications [5,17,73,109,133,138,139,157].

In summary of the published research works and the released software tools, the existing effort concentrates on the following aspects [112]: (1) low CPU time; (2) generality of applicability; (3) reliability; (4) simplicity of implementation; and (5) simplicity of topologies obtained. From the authors' interest, the aspects (2) and (5) are highlighted, because they could make topology optimization friendly to manufacturing. Topology optimization pursues the result optimality and generally produces complex topologies, which can only be manufactured through additive manufacturing (AM). However, in practice, AM is only an emerging technique while the conventional manufacturing methods such as machining and injection molding/casting still dominate the manufacturing sector. Therefore, coming back to the aspects (2) and (5), topology optimization problems should be formulated and solved with careful considerations of the manufacturing requirements, in order to generate simple topologies which are manufacturable through the conventional manufacturing methods.

The main body of this paper is organized as: Section 2 reviews the efforts to parameterize the topology design; Section 3 looks into the machining-oriented topology optimization methods which highlights two aspects, i.e. length scale control and geometric feature based design; Section 4 reviews the injection molding/casting-oriented topology optimization methods which highlights two aspects of part ejection and rib thickness control; In Section 5, future research directions are proposed and the underlying challenges and opportunities are discussed. At the end, the conclusion is given.

2. Parameterization

Topology optimization originates as a discretized computational design method. For this reason, it generates topology designs in tessellated and even blurred form, which may not be manufacturable or very costly to do so [12,24]. To make the topology design manufacturing-friendly, post-processing is usually required to identify, smooth and parameterize the structural boundary. Surface smoothness enables smooth tool path and thus the fast machining process. In contrast, a tessellated surface requires many tool path turnings and yet the ravines are non-machinable by economical cutters. Parameterization is also important because a smooth surface does not always guarantee good manufacturability. For instance, undercuts are non-machinable or require special tools. Therefore, further shape editing is generally required which needs to be facilitated by the parameterized surface definition.

A simple approach is to manually reconstruct the topology design through parameterized solid geometry modeling. However, because of the uncertainties of the manual operations, a following sizing/shape optimization is required to ensure the result optimality [18]. A more desirable approach is to automatically smooth and parameterize the topology design through an integrated optimization algorithm. Beneficially, design efficiency could be improved and the subsequent sizing/shape optimization may be eliminated. Therefore, many research efforts have been spent on this advanced