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Abstract
Porous structural design has attracted tremendous interest because of the advances in additive manufacturing and the superior characteristics of porous structures. This study presents a filter approach for porous structural design in the framework of single-scale density-based topology optimization. It in principle follows the idea to control porosity by limiting the local volume fraction of material. These local limits are usually incorporated into the optimization problem as a number of individual constraints or one condensed constraint. In contrast to the conventional constraint approach, a filter approach is proposed here to explicitly integrate these local limits into the material interpolation and have them automatically satisfied during the optimization iterations. A variety of numerical examples have been studied to validate the effectiveness of the filter approach.

Keywords: Topology Optimization, Porous Structure, Additive Manufacturing, Damage Tolerance, Porosity Control

1. Introduction
Because of the advances in additive manufacturing, porous infill design is targeted as one of the crucial issues [1], and porous structural design has received an increasing number of studies in the community of topology optimization. Particularly, two studies intentionally exploited porosity to improve buckling strength [2] and damage tolerance [3]. While both of these two studies relate to structural safety, the work in [3] is closely related to fail-safe design [4-5], which means the structure can still resist the design load when a local failure occurs. Compared with fail-safe design, porous structural design needs much less computation and therefore can potentially be used as a convenient way to improve fail-safe behaviour.

The proposed porous structural design method falls into the category of single-scale topology optimization, i.e. without separation of macro-scale structure and micro-scale material. The major advantage of single-scale optimization is that the whole porous structure is analyzed and optimized in one macroscopic scale, and thus it does not suffer from connection problem among different types of units encountered in multi-scale topology optimization. Furthermore, its numerical implementation is simple, since researchers in the community of topology optimization are familiar with single-scale topology optimization. For porous structural design, the major disadvantage of single-scale topology optimization is that its computation can be more expensive than multi-scale topology optimization. However, the required computing resources are available today. Solving a single-scale topology optimization problem for porous structural design with coarse and moderate resolution can be achieved on PC and high-resolution designs can be achieved with GPU [6] or cluster [7-8].

In single-scale topology optimization, several studies have been made to generate optimized porous structures based on a variety of approaches, for example, the SIMP method [9,3], the Level Set Method (LSM) [10-11], the Bi-Directional Evolutionary Structural Optimization (BESO) method [12] and Voronoi diagram based method [13-15]. The study in this paper is based on the SIMP method. Alexander and Lazarus [9] first applied a single-scale optimization method to analyze and optimize porous structures a whole body without separation of macro- and micro-scale. However, the porous structures in their study were still assumed to be periodic and layered. The authors claim that micro-structural details can vary in all directions when applying a number of local limits of material as studied in [16] for maximal length scale control. This was investigated by Wu et al. [3], where they applied single-scale topology optimization to design optimized porous infill structures approaching bone-like structures by using one condensed constraint based on [16]. The constraint approach in [16] was also adopted by Zhao et al. [12] to study biomechanical morphogenesis of the leaves and stalks of representative emergent plants based on the BESO method. These related studies have mainly focused on the constraint approach to control porosity. Just like overhang angle control can be realized by using both the constraint approach [17] and filter approach [18-19], it should also be possible to control porosity by using filter approach. A filter approach to control porosity not only provides an alternative to the constraint approach, but also opens new opportunities for future
studies such as a potential combination with other filter approaches for additive manufacturing [18-19]. The aim of this paper is to provide a novel filter approach for porous structural design. The idea is to integrate these local limits into the material interpolation and have them automatically satisfied in the optimization.

The paper is organized as follows. Section 2 introduces the filter approach. Section 3 presents the results of a benchmark example. Section 4 draws the conclusions.

2. Method

2.1 Formulation of the optimization problem

Firstly the standard minimum compliance problem is considered as follows

$$\begin{align*}
\min_{x} & \quad c(x) = u^T K u \\
\text{subject to:} & \quad K(x) u = f, \\
& \quad V(x)/V^* \leq \alpha, \\
& \quad 0 \leq x \leq 1.
\end{align*}$$

(1)

Where $x$ is a vector of design variables, $c$ denotes the compliance, $K$ is the global stiffness matrix, $u$ and $f$ are the global displacement and force vector, respectively, $V$ and $V^*$ are the material volume and design domain volume, respectively, and $\alpha$ is the prescribed volume fraction. The conventional optimization based on Eq. (1) does not necessarily produce desirable porous structures, though porous structures can appear in the results in case of large-scale topology optimization.

For porous structural design, the local percentage of material can be limited by imposing a number of local constraints. In a straightforward way, the optimization problem for porous structural design can be formulated as

$$\begin{align*}
\min_{x} & \quad c(x) = u^T K u \\
\text{subject to:} & \quad K(x) u = f, \\
& \quad V_e(x)/V_e^* \leq \eta, \ \forall e \\
& \quad V(x)/V^* \leq \alpha, \ \text{(optional)} \\
& \quad 0 \leq x \leq 1.
\end{align*}$$

(2)

where $V_e$ and $V_e^*$ are local material volume and local design domain volume measured in a prescribed neighborhood of each element $e$, respectively, and $\eta$ is the prescribed limit of local volume fraction of material. For porous structural design, the global volume constraint becomes optional, since the total material volume is already limited by the local volume constraints. For the sake of computational efficiency, the local constraints can be aggregated into one condensed constraint. This constraint approach was studied in [3] and [12] for porous structural design. The local constraints in Eq. (2) and their variants are referred to as constraint approaches for porosity control.

In contrast to the above constraint approaches, a filter approach for porous structural design is presented in this paper. For the filter approach, a major change to the optimization problem in Eq. (2) is that the local constraints are removed. The resulting optimization problem looks the same as Eq. (1) and therefore is not re-written here for brevity. It is emphasized that the global volume constraint in this case is also optional as discussed in Eq. (2). After removing these local constraints from the optimization problem, their effects are retained through a novel filter approach described as follows.

2.2 Filter approach for porous structural design

Previous studies have presented a number of filter approaches for different purposes, including minimal length scale control, maximal length scale control and overhang angle control. Here, the purpose of the new filter approach is to introduce and control porosity of the optimized design.

A flow diagram of the proposed filter approach is illustrated in Fig. 1. It consists of a standard filtering and projection step, an additional filtering and projection step, and one multiplication. The idea is that one element can become...
solid when it wants to become solid without porosity control, and it satisfies the local limit in case of porosity control. For the sake of an intuitive physical meaning, a uniform filter is currently used in the second filtering to accurately calculate the local percentage of material. It is noted that it is possible to use other types of filters such as PDE filter in the second filtering process. In the second projection, a so-called low-pass projection function is used. In a discrete form, it projects the scalar value below a prescribed threshold to one and the scalar value above the prescribed threshold to zero. In the numerical implementation, a smoothed form is used, which is defined based on the smoothed Heaviside step function. The threshold parameter in the second projection is chosen based on the prescribed limit of the local percentage of material.

Fig. 2 illustrates the function of the proposed filter approach. For a given structural feature (shown as solid), the filter approach can open a hole (shown as void) in the center of structural feature where the local volume fraction of material exceeds a prescribed limit, for example, 50%. It is seen that the filter approach can effectively modulate the design space such that porosity is introduced into the structure. Hence, the proposed filter approach is called porosity control filter or porosity filter in terms of its function.

Figure 1. A flow diagram of the proposed density filter approach for porosity control

Figure 2. Illustration of the proposed filter approach. A: the scalar field resulting from the first projection. B: the scalar field after applying the second filter. C: the scalar field after applying the second projection. D: the final scalar field obtained by multiplying the two projected fields, i.e. A and C. Black and white colors denote solid and void, respectively.
3. Numerical examples
To investigate the effectiveness of the proposed filter approach, a range of examples have been studied. For the sake of brevity, only a benchmark cantilever beam problem is reported here.

Fig. 3A shows the definition of the structural optimization problem, including design domain, boundary condition and external load. The objective is to find an optimized porous structure with minimum compliance. The design domain is discretized by using $400 \times 200$ elements for a coarse-resolution design and $800 \times 400$ elements for a moderate-resolution design. Fig. 3B and 3C display two representative designs obtained by using the proposed filter approach. These results show that the proposed filter approach is effective to obtain optimized porous structures. Fig. 4 shows the evolution of the optimized design during optimization iterations for Fig. 3C. It shows that the design converges to a black-and-white design in a smooth manner.

![Figure 3A](image1.png)

**Figure 3.** Porous structural design of a cantilever beam. A: definition of the design domain, boundary condition, and external load. B and C: two representative designs obtained by using the proposed filter approach to control porosity.

![Figure 4](image2.png)

**Figure 4.** Evolution of the optimized design during optimization iterations. The designs are consecutively numbered.

4. Conclusions
This study set out to investigate a filter approach for porous structural design in the framework of single-scale density based topology optimization. The numerical examples suggested the proposed filter approach can effectively control the porosity of the resulting structure. In future work, the porosity control filter proposed here can be combined with other filter approaches such as overhang angle control filter [18-19] to generate optimized self-supporting porous structures.
Acknowledgments
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References