ARTICLE IN PRESS

Advances in Engineering Software xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Advances in Engineering Software

journal homepage: www.elsevier.com/locate/advengsoft

Research paper

Uniform thickness control without pre-specifying the length scale target under the level set topology optimization framework

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ARTICLE INFO

Keywords:
Length scale control
Uniform thickness distribution
Level set
Topology optimization
Multi-objective

ABSTRACT

In the authors' earlier work [1], a component length scale control functional was proposed to regulate the topology evolution with uniform thickness distribution; however, the sensitivity result was numerically calculated with certain approximation. In order to make this functional better work for complex design problems, the sensitivity result is now analytically calculated with the aid of the structural skeleton-based non-signed distance level set field. More importantly, this component length scale control functional has been upgraded to eliminate the need of pre-specifying the length scale target. By using control functional instead of constraints, a benefit is that the structural performance and length scale control effect can be balanced by the weight factor, because it is not always necessary to strictly achieve the uniform thickness distribution while drastically compromising the structural performance. Therefore, this work studies the uniform thickness control in a multi-objective manner. Effectiveness of the proposed method is proved through a few 2D and 3D numerical case studies.

1. Introduction

Topology optimization has been extensively studied for several decades. It has demonstrated the power in addressing multi-disciplinary structural optimization problems and has been widely accepted by commercial CAE systems as an important module [2]. So far, there are mainly three branch methods for continuum topology optimization: the SIMP (Solid Isotropic Material with Penalization) [3], level set [4,5], and ESO (Evolutionary Structural Optimization) [6]. SIMP method uses the element densities as the topology variable which are continuously varied driven by the sensitivity information. Level set is an interface-based approach where the material/void or material/material interface is evolved based on the sensitivity information. ESO adopts the element densities as the design variable similar to SIMP method; distinctively, it employs the hard-kill strategies to remove materials and rewarding strategies to re-introduce materials (the Bi-directional ESO). A large number of publications can be found about these methods which proves their effectiveness in addressing a variety of topology optimization problems, including minimizing stress, maximizing stiffness, and maximizing frequency, etc. Related literature surveys can be found in [3,7,8]. On the other hand, topology optimization is still not fully-developed in several aspects, especially considering the manufacturability-related issues. In the other words, the output of topology optimization has often been criticized for being too organic, which are costly in manufacturing or even non-manufacturable. Tremendous efforts have been spent on fixing this problem and a review paper [9] was recently published which presents the state-of-art of the manufacturability-oriented topology optimization.

Among the many manufacturability-related issues, length scale control is a long-lasting and challenging topic tightly associated with part manufacturability. For instance, uniform component thickness distribution is especially meaningful for injection molding, which facilitates uniform cooling to reduce warpage-type part defect [1]. As for machining, the component length scale should not be too small in order to avoid the machining instability, and the void length scale should also be constrained to guarantee the machine tool accessibility [10]. So far, length scale control has mainly been explored under the SIMP [11] and level set [4,5] frameworks.

Under the SIMP framework, Poulsen [12] developed the local integral constraints to address the minimum length scale control of both the component and void phases, which principally checked the monotonic density variations. Zuo et al. [13] utilized a minimum hole size constraint to remove the small hole features from the topology design. Guest et al. [14] developed a circular density filter, which coupled with the Heaviside function, realized the minimum component length scale control. Later, in order to realize the length scale control of both the component and void phases, a modified double Heaviside projection was developed [15]. Sigmund [16] developed a series of morphology-

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http://dx.doi.org/10.1016/j.advengsoft.2017.09.013
Received 18 May 2017; Received in revised form 16 August 2017; Accepted 27 September 2017
0965-9978/

Please cite this article as: Liu, J., Advances in Engineering Software (2017), http://dx.doi.org/10.1016/j.advengsoft.2017.09.013

based density filters which realized both the single-phase and double-phase minimum length scale controls. However, as mentioned in the same paper, the sensitivity analysis of the double-phase minimum length scale control is costly, and its cost is even comparable with finite element analysis (FEA). Based on the erode and dilate operations, a robust topology optimization method [17–19] was developed, where multiple design realizations were evaluated and the worst case was optimized. The double-phase minimum length scale control can be achieved in the case that the multiple realizations maintain a consistent topology [17,19,20]. A limitation of this method is that multiple FEAs are performed in each optimization loop.

Other than the minimum length scale control, Guest et al. [21] realized the maximum component length scale control by restricting any circular areas in diameter of the maximum length scale not fully filled. Zhang et al. [22] realized the simultaneous maximum and minimum component length scale control through the structural skeleton based constraints.

Level set method is also effective in length scale control, especially given the signed distance information, which greatly facilitates the length scale measure and control. Chen et al. [23] and Luo et al. [24] employed a quadratic energy functional as part of the objective function, which successfully realized the strip-like topology design with controlled thickness. Liu et al. [1] developed a simplified length scale control functional to realize the close-to-uniform rib thickness distribution. Guo et al. [25] realized the concurrent maximum and minimum component length control through the structural skeleton based constraints which is principally similar to [22]. The signed distance information facilitated the narrow-band structural skeleton extraction and related global constraints were constructed to restrict the component length scales. Xia and Shi [26] modified the structural skeleton based method. The trimmed structural skeleton and the concept of maximal inscribable ball were employed to evaluate the length scale. Discrete point-based structural skeleton was extracted instead of a narrow band which facilitated the distance evaluation from skeleton. In this way, the length scale constraints were directly applied to the structural boundary points. Allaire et al. [27] explored the length scale control in depth under different schemes of maximum length scale only, minimum length scale only, and the simultaneous control. A few different-typed constraints and penalty functional were compared and discussed. Zhang et al. [28] recently developed the component minimum length scale control method based on the level set-based Moving Morphable Component (MMC) method. Wang et al. [29] realized the component length scale control through addressing the contour-offset based constraints. Very recently, Liu et al. [10] proposed the minimum void length scale control method which constrained the void length scales by double lower bounds, so that the topology design can be milled by a rough-to-finish process. To the best of the authors' knowledge, this is the only work conducted so far to control the void length scale under the level set framework. Literature surveys on length scale control can be found in [9,30].

Even extensively studied, there is still room for further development of the length scale control technique. This research work is conducted under the level set framework, and thus, a discussion is made below to present the pros and cons of the existing level set-based length scale control methods. Contributions of this paper is highlighted, as well.

(i) So far, the length scale control has been realized in two ways: by using constraints or penalty functional. Generally, by setting the constraints, the derived component length scale can accurately fall into the designated range; while by using the penalty functional, the component length scale is loosely constrained and may slightly deviate from the pre-specified length scale value; see [23]. In practice, it is not always necessary to strictly restrict the length scale at the cost of over compromised structural performance. Therefore, we use the penalty functional and formulate the optimization problem into a multi-objective form, where a series of design solutions with differently balanced structural performance and length scale control effect could be derived. The length scale control functional previously proposed in [1] is adopted, which employs a simple domain integration expression and its physical meaning is easy to understand.

(ii) Different from [1], the length scale control functional is solved in a more accurate manner, which works well on complex design problems.

(iii) To realize the multi-objective purpose, a weight factor is added to the length scale control functional, and three strategies are explored to control the variation of the weight factor to derive the best design effect.

(iv) The existing length scale control methods generally pre-specify the targeted length scale value or range. However, it is non-trivial to manually determine this target, which at most times, relies on the trial-and-error approach. Therefore, this paper addresses this issue by upgrading the length scale control functional proposed in [1], which still supports the uniform thickness distribution while the need for pre-specifying the length scale target is eliminated.

2. Level set based length scale control

2.1. Basic introduction to level set function

Level set function, $\Phi(\mathbf{X})$: $R^n \mapsto R$, represents any structure in the implicit form, as:

$$\begin{cases} \Phi(\mathbf{X}) > 0, & \mathbf{X} \in \Omega/\partial\Omega \\ \Phi(\mathbf{X}) = 0, & \mathbf{X} \in \partial\Omega \\ \Phi(\mathbf{X}) < 0, & \mathbf{X} \in D/\Omega \end{cases} \tag{1}$$

where Ω represents the material domain, D indicates the entire design domain, and thus D/Ω represents the void.

Generally, the level set field satisfies the signed distance regulation through solution of Eq. (2), through which absolute of the level set value at any point represents its shortest distance to the structural boundary and the sign indicates the point to be either solid (> 0), or void (< 0).

$$|\nabla\Phi(\mathbf{X})| = 1 \tag{2}$$

2.2. Level set based topology optimization

Under the level set framework, the compliance-minimization topology optimization problem is formulated in Eq. (3).

$$\begin{aligned} &Min. \quad J(\mathbf{u}, \Phi) = \int_D \frac{1}{2}\mathbf{De}(\mathbf{u})\mathbf{e}(\mathbf{u})H(\Phi)d\Omega \\ &s.\ t. \quad a(\mathbf{u}, \mathbf{v}, \Phi) = l(\mathbf{v}, \Phi), \ \forall\, \mathbf{v} \in U_{ad} \\ &\qquad\quad \int_D H(\Phi)d\Omega \le V_{max} \\ &a(\mathbf{u}, \mathbf{v}, \Phi) = \int_D \mathbf{De}(\mathbf{u})\mathbf{e}(\mathbf{v})H(\Phi)d\Omega \\ &l(\mathbf{v}, \Phi) = \int_D \mathbf{pv}H(\Phi)d\Omega + \int_D \tau\mathbf{v}\delta(\Phi)|\nabla\Phi|d\Omega \end{aligned} \tag{3}$$

In Eq. (3), the structural compliance (sum of the strain energy densities) is to be minimized. $a(\mathbf{u}, \mathbf{v}, \Phi)$ is the energy bilinear form and $l(\mathbf{v}, \Phi)$ is the load linear form, which together form the weak form of the governing equation. For the symbols in the problem formulation, $\mathbf{u}$ is the deformation vector, $\mathbf{v}$ is the test vector, and $U_{ad} = \{\mathbf{v} \in H^1(\Omega)^d | \mathbf{v} = 0 \ on\ \Gamma_D\}$ is the space of kinematically admissible displacement field; $\mathbf{D}$ is the elasticity tensor and $\mathbf{e}(\mathbf{u})$ is the strain; V_{max} is the upper bound of the material volume; $H()$ and $\delta()$ are the Heavisde function and the Dirac Delta function, which are applied to realize the domain and boundary integrations, respectively.

The Augmented Lagrange Multiplier method is applied and the adjoint sensitivity analysis is performed to solve this optimization