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Length scale control for structural optimization by level sets

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Abstract

The present paper proposes a novel structural optimization method to achieve length scale control on optimal designs in the level set framework. Size constraints are established with the use of the offset of structural boundaries as well as that of level set contours. Thus, the method requires no geometric skeleton during the optimization iterations, which would effectively improve computational efficiency. In addition, the size constraints are imposed in an explicit integral-type manner, thus facilitating the numerical implementation. The approach also enables to prescribe the minimum/maximum required member sizes to be precise values. Various design problems are solved to demonstrate the validity of the proposed method.

Keywords: Structural optimization; Level set method; Manufacturing constraint; Length scale control; Member size control

1. Introduction

Improving performance of engineering structures is always the target of designers and engineers. However, the conventional design strategy that relies on designers' engineering experience is not in tune with today's computing science. Advanced by the rapid development of numerical computational-based design methodology, structural topology optimization has opened up a new way to create novel but more powerful structures. Up to date, the topology optimization has received extensive attention and the readers are referred to [1,2] for a review of the latest development in this field. Meanwhile, significant advances of additive manufacturing technology have made it possible to fabricate novel-conceptual structures with arbitrary geometric-complex configurations. For instance, the 3D printing technique has been successfully used to fabricate super-strength lightweight cellular structures [3].

It is essentially important to consider manufacturing constraints during the design stage, not only to improve processing efficiency and reduce machining error but also to prevent undesirable engineering designs. In the field of topology optimization, a number of manufacturing constraints have been developed. For instance, the non-overlap constraint was imposed for an integrated design of a continuum structure embedded with movable shape-preserved

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components [4–6]. Another example is to optimize the layout and the number of fabrication supports for a 3D-printed structure [7,8]. Some other manufacturing constraints include the drafting mold constraint [9], the manufacturing error constraint [10], and the feature control constraint [11].

The length scale control is of great importance in the field of engineering design. As a matter of fact, the minimum and maximum member sizes significantly determine the overall performance of the designed structures, such as the stress distribution and the critical load. A simple example is that a circular rod would bear higher tension/compression stresses by reducing its radial size. In addition, the minimum member sizes will effectively influence the fabrication complexity and accuracy from a manufacturing point of view. For example, since the resolution of a 3D printer is fixed in advance, designed structures without small-sized details would be generally preferred. Thus, an effective design approach should be developed to possess the ability to control the minimum/maximum structural sizes of the optimal designs.

It has been a long-standing effort to design novel structures with length scale control in topology optimization. Most early studies working on this issue utilized the density distribution-based methods. For instance, Zhou et al. [12] applied a slope constraint on each pair of two adjoint elements for generating optimized structures free of small-sized members. Poulsen [13] suggested an explicit monotonicity-based minimum length scale constraint in optimization. Guest et al. [14] proposed a projection method to achieve the minimal structural size control, where the minimum member size would not be smaller than the radial size of the projection domain. This technology was also extended to constrain the minimum length scale on different phases [15] and the maximum member size [16] of the optimized solutions. The independent point-wise density interpolation (iPDI) algorithm [17] produces a similar effect. More recently, Zhou et al. [18] proposed a new method by constraining the minimum structural length scale with a density-based functional indicator. All these density-based approaches can also yield checkerboard-free and mesh-independent optimal structures, since the small features of the obtained designs have been prohibited.

Recently, the level set topology optimization methodology has been developed as one of the most popular design methods. The underlying concept of the approach is to evolve structural boundaries by given velocities, and then the topological configuration changes by emerging and splitting of the boundaries. As it was first proposed by Osher and Sethian [19] for capturing dynamic boundaries, the level set method was introduced into the field of structure design [20–22]. Since then, a variety of level set methods have been developed [23–27] and a recent review on these methods is referred to [2]. The level set model possesses its unique advantage of defining distinct geometric interface between different material phases. This would greatly facilitate the geometry modeling process of the optimal designs using modern CAD software. In addition, the exact definition of the interface significantly improves the numerical accuracy when solving an interface-evolving problem, e.g. in the field of materials science [28] and computer graphics [29].

To date, a number of level set methods have contributed to design structures with the length scale constraints. Chen et al. [30] realized minimum feature size control in topology optimization by incorporating a non-local quadratic energy functional into the objective function. The restriction on the global energy functional can effectively eliminate small-sized members in the optimal designs. A similar approach was developed by Luo et al. [31] to get hinge-free compliant mechanisms. In the work of Yamada et al. [32], optimized results with uniform-sized members were obtained using a similar approach. Two issues may be encountered in these methods. One is that they lack the ability to set the required minimum structural size to an exact value, since no explicit geometric information is provided. The other one is that all these studies did not discuss how to restrict the maximum structural size of the optimized solutions. To overcome these difficulties, an explicit geometric size control algorithm was proposed by Guo et al. [33]. The basic idea of the approach is to impose the length scale constraints by restricting the minimum or/and maximum value of a signed distance function, which is evaluated on the skeleton of the optimized structures. The method can simultaneously and exactly control the minimum and maximum structural size of the optimal solutions. Allaire's group [34,35] suggested a more general scheme where a minimum size constraint was imposed on void regions as well. Xia and Shi [36] further improved the algorithm by using the concept of the smallest and biggest maximal inscribable balls, where the structural sizes were controlled by constraining the distance from structural boundaries to the skeletons. To impose the explicit size constraints, the geometric skeleton of the solid regions is typically required in these methods. In addition, a large number of point-wise constraints should be transferred into a global integral one by quadratic penalty functionals.

This paper is to propose a novel structural optimization method to control the minimum/maximum structural sizes of the optimal designs under the framework of the level set approach. The proposed size constraints are developed