Accepted Manuscript

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PII: S0045-7825(18)30213-5
DOI: https://doi.org/10.1016/j.cma.2018.04.034
Reference: CMA 11885

To appear in: *Comput. Methods Appl. Mech. Engrg.*

Received date : 17 November 2017
Revised date : 15 April 2018
Accepted date : 18 April 2018

Please cite this article as: Y. Liu, Z. Li, P. Wei, W. Wang, Parameterized level-set topology optimization method considering symmetry and pattern repetition constraints, *Comput. Methods Appl. Mech. Engrg.* (2018), https://doi.org/10.1016/j.cma.2018.04.034

Parameterized Level-Set Topology Optimization Method Considering Symmetry and Pattern Repetition Constraints

Yang Liu [a], Zuyu Li [b], Peng Wei [a,1], Wenwen Wang [a]

[a] *State Key Laboratory of Subtropical Building Science, School of Civil Engineering and Transportation, South China University of Technology, 381 Wushan Rd, Tianhe, Guangzhou, Guangdong, China*
[b] *Architecture and Civil Engineering Institute, Guangdong University of Petrochemical Technology, Maoming, Guangdong, China*

ABSTRACT

Symmetry and repetitive patterns are very common in both natural and artificial structures. Design with symmetry and pattern repetition (SPR) can be very useful in practical engineering. In this paper, we discuss a new optimal structural design method considering SPR constraints. The basic idea consists in combining a parameterized level-set method together with radial basis function (RBF) interpolation strategy, which allows for decoupling RBF knots from the finite element (FE) analysis mesh. The merits of the decoupled manner are that RBF knots can be mapped independently on regular or irregular design domain, and SPR constraints can be imposed by simply building a bijective relationship between RBF knots regardless of analysis mesh. Furthermore, due to parameterization of the level-set function, there are fewer numerical manipulations that need to be implemented than the conventional level-set method during the optimization process. Several numerical examples are presented to show feasibility and effectiveness of the proposed method.

KEYWORDS

Symmetry and pattern repetition; Unstructured mesh; Parameterized level-set method; Topology Optimization

1. Introduction

Symmetry and pattern repetition (SPR) are often used in practical engineering. In microstructures, periodic patterns are widely applied to achieve certain functional properties. In the case of macrostructures, due to their large sizes, they are often decomposed into several relatively smaller components with the same or similar patterns to satisfy manufacturing, transportation, installation, maintenance, recycling or other practical constraints. To date, SPR have reported a broad range of applications in engineering [1-8].

SPR can be achieved in structural design through experiences, experiments or numerical simulations. Recent years have seen improvement in structural design thanks to the development of topology optimization. Topology optimization is a powerful tool for solving a material distribution problem and generating an optimal topology from many physical perspectives [9]. Widely used methods can be roughly classified into three categories: the density-based methods such as the SIMP model [10, 11] and the homogenization method [12, 13]; the Eulerian methods such as the phase field method [14-16] and the level-set method [17-21]; the Lagrangian methods such as the DSC method [22] and the MMC method [23, 24].

In the field of microstructures design, the geometrical configuration pattern of a unit cell is optimized and microstructures are assembled periodically to form macrostructures with certain functional properties [25]. The geometrical patterns of microstructures can also be designed with graded configurations aimed at achieving gradually-changed effect of macrostructures [26, 27]. The design of macrostructures with periodic patterns is different from the material design of microstructures in that they have much larger length-scales than the microscopic cells that have characteristic sizes. Zhang and Sun [28] examined scale-related effect of cells and achieved both designs of microstructures and macrostructures by changing the length-scales of cells. Huang and Xie [29] studied the similar scale-dependent effect of periodic structures using the BESO technique [30, 31]. A further research of Xie et al. [32] found that the optimized microstructures would converge to a certain pattern as the length-scales of cells decrease. Chen et al. [33] presented a unified optimization algorithm to simultaneously address the stiffness and conductivity criteria of multifunctional structures with pattern repetition. Sylvia et al. [34] proposed a FGM-SIMP model for optimization of functional graded materials (FGMs) considering SPR constraints. Stromberg et al. [35] explored the application of pattern repetition and gradation for the conceptual design of buildings. Recently Liu et al. [36] introduced optimal design of lattice structures with graded patterns using an explicit topology optimization approach. Further, there were attempts to implement concurrent design of both microstructures and macrostructures in a two-scale analysis manner. The two-scale analysis was performed in a decoupled way for hierarchical optimization [37, 38], and a coupled way for nonlinear multi-scale optimization [39, 40]. However, patterns may vary spatially from cell to cell for the scale separation analysis. To address connectivity issue between patterns, Alexandersen and Lazarov [41] and Li et al. [42] combined the fully-refined details of microstructures in the macroscopic displacement analysis to ensure the connectivity. Cramer et al. [43] presented a shape interpolation scheme to produce macrostructures with a series of connectable isotropic microstructures that were optimized in advance. Recently Wang et al. [44] developed a shape metamorphosis technology to guarantee the connectivity between neighboring microstructures with a similar material distribution pattern along their interfaces. It is noted that most previous works were performed on regular

1 Corresponding author.
E-mail address: ctpwei@scut.edu.cn (P. Wei).