

Research Article

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Computational Multiscale Methods for Nondivergence-Form Elliptic Partial Differential Equations

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Abstract: This paper proposes novel computational multiscale methods for linear second-order elliptic partial differential equations in nondivergence form with heterogeneous coefficients satisfying a Cordes condition. The construction follows the methodology of localized orthogonal decomposition (LOD) and provides operator-adapted coarse spaces by solving localized cell problems on a fine scale in the spirit of numerical homogenization. The degrees of freedom of the coarse spaces are related to nonconforming and mixed finite element methods for homogeneous problems. The rigorous error analysis of one exemplary approach shows that the favorable properties of the LOD methodology known from divergence-form PDEs, i.e., its applicability and accuracy beyond scale separation and periodicity, remain valid for problems in nondivergence form.

Keywords: Nondivergence-Form Elliptic PDE, Localized Orthogonal Decomposition, Numerical Homogenization, Finite Element Methods

MSC 2020: 35J15, 65N12, 65N30

1 Introduction

In this work, we consider linear second-order elliptic partial differential equations of the form

$$A : D^2 u + b \cdot \nabla u - cu := \sum_{i,j=1}^n a_{ij} \partial_{ij}^2 u + \sum_{k=1}^n b_k \partial_k u - cu = f \quad \text{in } \Omega, \quad (1.1)$$

posed on a bounded convex polyhedral domain $\Omega \subset \mathbb{R}^n$, $n \geq 2$, with a right-hand side $f \in L^2(\Omega)$, subject to the homogeneous Dirichlet boundary condition

$$u = 0 \quad \text{on } \partial\Omega, \quad (1.2)$$

where $A = (a_{ij})_{1 \leq i,j \leq n} \in L^\infty(\Omega; \mathbb{R}_{\text{sym}}^{n \times n})$, $b = (b_k)_{1 \leq k \leq n} \in L^\infty(\Omega; \mathbb{R}^n)$, and $c \in L^\infty(\Omega)$ are heterogeneous coefficients such that A is uniformly elliptic, $c \geq 0$ almost everywhere in Ω , and the triple (A, b, c) satisfies a (generalized) Cordes condition. Our main objective in this paper is to propose and rigorously analyze a novel finite element scheme for the accurate numerical approximation of the solution to the multiscale problem (1.1)–(1.2), a task we will refer to as numerical homogenization, by following the methodology of localized orthogonal decomposition (LOD) [31, 32]. It is worth mentioning that we are working in a framework beyond periodicity and separation of scales.

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