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Optimal design of multiphase composites under elastodynamic loading

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Highlights

- Developing an efficient computational algorithm to solve multimaterial topology optimization problems under elastodynamics loading conditions.
- The implementation complexity of the presented algorithm is independent to the number of phases.
- The presented algorithm generates near 0–1 topologies without regard to the number of phases.

Abstract

An algorithm is proposed to optimize the performance of multiphase structures (composites) under elastodynamic loading conditions. The goal is to determine the distribution of material in the structure such that the time-averaged total stored energy of structure is minimized. A penalization strategy is suggested to avoid the checkerboard instability, simultaneously to generate near 0–1 topologies. As a result of this strategy, the solutions of presented algorithm are sufficiently smooth and possess the regularity of H^1 function space. A simple method for the continuum adjoint sensitivity analysis of the corresponding PDE-constrained optimization problem is presented. It is general and can be easily applied to a wide range of alternative problems. The success of the introduced algorithm is studied by numerical experiments on two-dimensional model problems for different numbers of phases. According to numerical results, the objective functional is reduced monotonically with iterations. Moreover, the final topologies at the optimal solutions are near 0–1. The dynamic behavior of optimal designs is compared to that of initial ones to show the impact of optimization on the performance of structures.

Keywords: Adjoint sensitivity analysis; Multimaterial topology optimization; Optimal design; Regularization; Stress waves

1. Introduction

Many engineering structures experience elastodynamic loading conditions during their lifetime period, which results in the propagation of stress waves in the structures. The interaction of structures with stress waves is an important factor that should be taken into account during their design stage. Topology optimization [1] is a standard method to

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find unknown layout of structures to improve their performances. Topology optimization of structures under static loading conditions has been well studied in the literature c.f. [1,2]. Regarding topology optimization under dynamic conditions, many of available works have been focused on the optimal design of structures based on the eigenfrequency analysis, for instance to maximize the smallest eigenvalue of structure under free vibration (c.f. [3–21]). In fact, in these works, the quasi steady-state conditions were assumed for the stress waves and so the displacement field was computed by solving a Helmholtz-like PDE in the frequency domain. However, under the actual dynamic loading conditions, the interaction of stress waves with the material inhomogeneities and solid boundaries leads to a complex space–time wave pattern in the body. As a result, the assumption of quasi steady-state conditions and decomposition of stress waves into the pressure and shear components is not sufficiently feasible [22,23]. A natural solution to cope this limitation is the space–time analysis of elastic waves in structures.

There are a few works on topology optimization of structures based on the time-domain analysis (c.f. [24]). Using the homogenization method, the two dimensional time-domain topology optimization problem has been considered in [25]. The objective functional, to be minimized, in this work was the time-averaged dynamic compliance of structure in a finite time-windows. The three-dimensional form of this problem has been studied in [22] to find the optimal layout of functionally graded materials. Mono-dimensional topology optimization under transient loading has been considered in [26] for the optimal design of inhomogeneous solids that exhibit desired band-gap structures. The optimal determination of space–time material layout was considered in [27]. In this work, the dynamics of structure was governed by the one dimensional linear wave equation that includes a damping term. The corresponding objective functional depends on the gradient and time derivative of the displacement field. Later, this problem has been extended to higher dimensions in [28,29]. A similar problem, however without the damping term, has been considered in [30]. The optimization of space–time material layout for the one-dimensional wave propagation problem with varying mass and stiffness parameters has been investigated in [31,32]. The topology optimization of low contrast two-phase composites subjected to the wave equation has been studied in [33]. By assuming the low contrast between phases, the authors used a second order asymptotic expansion with respect to the small amplitude of the phase coefficients that helps them to rigorously prove the existence of solution for this problem by means of the relaxation theory (c.f. [2]). These authors examined several variants of objective functionals and supported their theory by several numerical experiments. In [34], it has been experimentally and theoretically shown that the stress-waves in solids can be controlled through imposing graded changes in the material properties. Taking inspiration from this work, topology optimization based on the homogenization method has been adapted in [35] for the optimal management of stress waves in solids. In this work, different objective functionals have been introduced to find the optimal layout of a rank-N laminated composite structure for damping, redirecting and focusing of elastic stress waves. Topology optimization of energy dissipating structures under impact loading is studied in [36] for rate-independent elastoplastic materials.

Recently, there has been an increasing interest in solving topology optimization problems using more than two phases [37,38]. It is particularly attractive for the optimal design of engineering structures under transient loading conditions. An interesting question in this context is that whether increasing the number of contributing phases can improve the dynamic performance of structures. There are several efforts on the multimaterial topology optimization under static loading conditions. For instance, it has been solved by the MMA method [39–42], optimality criteria approach [37], level set method [43–52], phase-field approach [38,53–58], discrete material optimization method [59–61] and shape function parameterization scheme [62–64].

According to our knowledge, there is no work on the time-domain multimaterial topology optimization under elastodynamic loading conditions. The goal of present study is to introduce a numerical algorithm to solve multiphase topology optimization problems under elastodynamics loading conditions. The remainder of this paper is organized as follows. The mathematical formulation of the corresponding topology optimization problem is presented in the next section. According to our numerical experiments to attain near 0–1 topologies, i.e. having the sufficient contrast between phases, is difficult in practice, because the optimal solutions tend to smear the interfaces between phases. For instance, using the SIMP penalization approach does not lead to satisfactory results. Following [38], the penalization of problem based on the combination of SIMP and phase-field approaches is presented in Section 2, to cope the mentioned difficulty. Section 3 presents the first order necessary optimality conditions corresponding to the penalized optimal design problem. The minimization algorithm based on the regularized projected steepest descent method is presented in Section 4. Section 5 briefly mentions the discretization schemes used for the numerical solution of this optimal design problem. Section 6 is devoted to the evaluation of presented algorithm by means of numerical experiments. Finally, Section 7 summarizes this paper.