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Design of piezoelectric actuators using a multiphase level set method of piecewise constants

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ABSTRACT

This paper presents a multiphase level set method of piecewise constants for shape and topology optimization of multi-material piezoelectric actuators with in-plane motion. First, an indicator function which takes level sets of piecewise constants is used to implicitly represent structural boundaries of the multiple phases in the design domain. Compared with standard level set methods using n scalar functions to represent 2^n phases, each constant value in the present method denotes one material phase and 2^n phases can be represented by 2^n pre-defined constants. Thus, only one indicator function including different constant values is required to identify all structural boundaries between different material phases by making use of its discontinuities. In the context of designing smart actuators with in-plane motions, the optimization problem is defined mathematically as the minimization of a smooth energy functional under some specified constraints. Thus, the design optimization of the smart actuator is transferred into a numerical process by which the constant values of the indicator function are updated via a semi-implicit scheme with additive operator splitting (AOS) algorithm. In such a way, the different material phases are distributed simultaneously in the design domain until both the passive compliant host structure and embedded piezoelectric actuators are optimized. The compliant structure serves as a mechanical amplifier to enlarge the small strain stroke generated by piezoelectric actuators. The major advantage of the present method is to remove numerical difficulties associated with the solution of the Hamilton–Jacobi equations in most conventional level set methods, such as the CFL condition, the regularization procedure to retain a signed distance level set function and the non-differentiability related to the Heaviside and the Delta functions. Two widely studied examples are chosen to demonstrate the effectiveness of the present method.

1. Introduction

Microactuators are now becoming increasingly popular as they offer significant potential in a broad range of engineering applications. Amongst a variety of actuators, piezoelectric material based actuation has been considered as one of the most appealing means due to its favorable characteristics, e.g. high energy densities in nanometer range, fast response time and large loading capacity [15,29]. It is well known that the piezoelectric actuator uses the inverse rather than the direct piezoelectric effect to convert electric energy to mechanical actuation. This research concentrates on the design of piezoelectric

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actuators capable of generating in-plane motion rather than out-of plane motion. The devices with in-plane motion are more suitable for micro-mechanical systems [1] because of the consideration of the microscale packaging process.

A range of methods have been developed for the design of piezoelectric actuators in the context of smart structures. As noted in [15], a large portion of current research, however, either concentrates on optimal design of host compliant structure with one or more pre-determined actuators [40,11] or concerns with the design of the actuator with given structure [18,42]. It is noted that both design methods impose a limitation on the optimality of the piezoelectric actuation system [15]. Since the performance of a smart actuator is dependent on the coupling between a host structure and its attached piezoelectric actuators [8,10], a more potential way is to simultaneously optimize both piezoelectric actuators (placements, shapes, topologies, etc.) and their host structure (shape and topology) via a numerical process of distributing the elastic material, the piezoelectric material and the void material in the design domain at the same time. Thus, the piezoelectric actuator considered in this work is such a device in which a passive compliant host structure is actuated by embedded piezoelectric elements to generate in-plane motions at specific positions. Since the actuators designed in this way is usually subject to small strain stroke [40], the host structure serves as a compliant mechanical amplifier to enlarge the small stroke produced by piezoelectric materials [19,11,22]. A piezoelectric actuator can therefore be regarded as an electromechanically actuated compliant mechanism [17] capable of accomplishing complex in-plane movements without the use of conventional joints and pins. Such smart actuators are particularly suitable for transmitting nanometer to micrometer displacement in micro-mechanical systems (MEMS) [1]. Hence, this study aims to develop a systematic design method for multiphysics and multi-material smart actuators with in-plane motions using a new shape and topology optimization method.

The goal of topology optimization is to find the optimal distribution of a given amount of material via an iterative numerical process in an extended fixed domain to extremize a specified objective function [14,5]. The field of topology optimization has experienced considerable advance during the past decade with development of different methods, e.g. the homogenization method [4], the SIMP method [55,28,6], the evolutionary structural optimization (ESO) method [53], the level set method including both the standard level set-based methods [37,33,47,2] and the parameterization or equivalent level set methods [3,16,49,26,27,50]. Amongst a variety of possible applications of the topology optimization method, the design of piezoelectric actuators has been very promising [11,8,10,20]. However, most current studies are mainly concerned with single material design and the research on multi-material design is relatively rare. Hence, only a few available publications are on multi-material shape and topology optimization problems, which mostly employ material distribution (Homogenization or SIMP) methods in conjunction with a rule of mixtures to implement multiphase modeling. For instance, Sigmund [39] studied a hybrid power-law interpolation scheme to describe the effective material properties for electrothermomechanical multiphysics actuators, by combining the Hashin–Shtrikman bounds with the standard power-law penalization method. Buehler et al. [8] used the homogenization method to implement the simultaneous design of a given amount of non-piezoelectric and piezoelectric material in the design domain with un-pre-determined sizes and shapes. Carbonari et al. [10] used a SIMP based power-law interpolation scheme to address the placements of the piezoelectric materials and the topology of the flexible structure, but it was reported that the material interpolation model applied suffers from several well-recognized drawbacks [39]. There are still two fundamental issues [48] that are in debate when applying the material distribution method to the multi-material topology optimization: the material interpolation scheme and the ill-posedness of the optimization problem.

There have been several methods for the multiphase motions using level sets [54,12,46,48,23,24]. Vese and Chan [46] proposed a level set multiphase scheme to implement image segmentation using the Mumford and Shah model, which requires log n level set functions for n segments or phases in the piecewise constant case. Wang and Wang [48] studied a "color" level set model for the shape and topology optimization of multiphase material problems [48] based on the standard level set method [32,36,34], which represents 2^n different material phases using n level set functions. However, this method may lead to some empty regions if the number of the multiple phases is not exactly equal to 2^n, because in this case the total number of the phases is over estimated. The standard level set-based methods suffer from several numerical difficulties related to the implementation of the Hamilton–Jacobi equation [49,26]. Tai et al. [23,24,44] proposed a piecewise constant "level set" method (PCLSM) to identify curves separating regions into different phases in Mumford–Shah image segmentation, which only uses one indicator function taking piecewise constants rather than several level set functions to represent multiple phases. Wei and Wang [50] studied the basic application of the piecewise constant "level set" method [23,24] to structural shape and topology optimization problems, but it is merely concentrated on structural stiffness designs involving one single material. However, the most attractive feature of PCLSM is to represent and identify the boundaries of the multiphase motions [54,35,46].

Therefore, this study presents a shape and topology optimization method for multiphysics and multi-material piezoelectric actuators using PCLSM [23,24,43,44]. An indicator function consisting of several piecewise constants is applied to model different regions in the entire design domain for multi-material smart actuators. Each constant value function involved in the level set function is used to uniquely represent one material phase, and n different phases require n piecewise constant value functions. A minimization functional is defined as a smooth energy term to formulate the optimization problem with the specified constraints. In doing so, the design optimization is converted into a process of renewing all the constant value functions using a semi-implicit AOS algorithm [25,52] to descend the design sensitivity [27], until the shape and topology of both host structure and the locations, shapes and topologies of piezoelectric materials are optimized in the same design domain simultaneously. The major characteristic of PCLSM [24,23] is to remove the connection between the level set functions and re-initializations of the signed distance function, to totally relax the time step limitation imposed by the CFL condition, and