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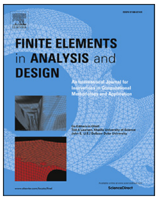

On the effect of fluid-structure interactions and choice of algorithm in multi-physics topology optimisation

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ABSTRACT

This article presents an optimisation framework for the compliance minimisation of structures subjected to design-dependent pressure loads. A finite element solver coupled to a Lattice Boltzmann method is employed, such that the effect of the fluid-structure interactions on the optimised design can be considered. It is noted that the main computational expense of the algorithm is the Lattice Boltzmann method. Therefore, to improve the computational efficiency and to assess the effect of the fluid-structure interactions on the final optimised design, the degree of coupling is changed.

Several successful topology optimisation algorithms exist with thousands of associated publications in the literature. However, only a small portion of these are applied to real-world problems, with even fewer offering a comparison of methodologies. This is especially important for problems involving fluid-structure interactions, where discrete and continuous methods can provide different advantages.

The goal of this research is to couple two key disciplines, fluids and structures, into a topology optimisation framework, which shows fast convergence for multi-physics optimisation problems. This is achieved by offering a comparison of three popular, but competing, optimisation methodologies. The needs for the exploration of larger design spaces and to produce innovative designs make meta-heuristic algorithms less efficient for this task. A coupled analysis, where the fluid and structural mechanics are updated, provides superior results compared with an uncoupled analysis approach, however at some computational expense. The results in this article show that the method is sensitive to whether fluid-structure coupling is included, i.e. if the fluid mechanics are updated with design changes, but not to the degree of the coupling, i.e. how regularly the fluid mechanics are updated, up to a certain limit. Therefore, the computational efficiency of the algorithm can be considerably increased with small penalties in the quality of the objective by relaxing the coupling.

1. Introduction

Topology optimisation of continuum structures has seen an exponential increase in publications [1] since it was first proposed almost three decades ago [2]. Today it has matured to a level where it is becoming a common design tool used by industry. Here, the main idea is to find the optimal distribution of material in a predefined design domain considering an objective function and constraints. In the topology optimisation literature, one finds that a wide variety of objective functions have been considered, showing a diversity of application that spans to almost all fields of engineering and design [3–5]. However, design-dependent pressure loading problems are still uncommon [6,7], with little discussion on the effect of the degree of coupling on the design and no comparison between optimisation methods.

Traditional topology optimisation methods seek to find the maximum stiffness with a predefined fixed loading [8–10]. However, there are many applications in which the load location and magnitude vary as the design changes during the optimisation process. Recently, the authors of this study developed a Bi-directional Evolutionary Structural Optimisation (BESO) algorithm that is coupled to a Lattice Boltzmann method (LBM) for the optimisation of design-dependent pressure loading problems [6]. The method was applied to an industry design problem: namely, the design of micro fluidic mixers. It was found that the

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computational time required to solve such problems exceeded a reasonable level for use in the preliminary design stages [6]. Furthermore, only a BESO algorithm was employed. Hence, this study proposes relaxing the degree of coupling between the LBM and finite element analysis (FEA) to quantify the impact of this coupling on the objective function value found and computational efficiency of the algorithm. Moreover, other types of topology optimisation methods, both continuous and discrete, are implemented into the framework. The results of the different optimisation methods indicate that they have different outcomes. Therefore, the advantages of the different optimisation methods are identified.

The examples considered in this study are further complicated by the Fluid-Structure Interactions (FSI) present between the structure being optimised and the flow, making the design dependent on the pressure loading from the fluid. The challenge in optimising a structure with an applied pressure load lies in determining the loading surface on which the pressure acts. This becomes more difficult for traditional density-based topology optimisation methods, such as Solid Isotropic Material with Penalisation (SIMP) [11] and Homogenization [2]. In these methods, the structural boundaries, and hence loaded surfaces, are not explicitly defined due to the presence of intermediate density elements [12]. Therefore, in this study, a novel filter scheme is developed such that the structural boundary at each iteration is determined.

In this article, extended BESO, level-set and SIMP algorithms are applied to the design of micro fluidic mixers considering FSI. A three-dimensional (3D) LBM is used as the flow solver with two fluid species, extending beyond the basic two-dimensional (2D) Stokes flow used in the literature. Multiple optimisation techniques, both continuous and discrete, are compared, evaluating the benefits of these methods for design-dependent pressure-loaded problems. With the proposed framework, the design of structures subjected to fluid pressure loads can be easily implemented with high fidelity algorithms incorporated at the conceptual and detailed design phases, efficiently coupling multiple physical models. Furthermore, insight is given into the advantages and disadvantages of using different optimisation techniques.

The rest of this article is organised as follows. Sect. 2 outlines the necessary background and literature for the manuscript. Sect. 3 presents the governing equations for the fluid and structural models. Sect. 4 presents the topology optimisation problem and the various topology optimisation methods employed in this work. In Sect. 5, the methodology for coupling the multiple disciplines and extending the optimisation methods to the fluid-structure problem is outlined. The results from the three different topology optimisation algorithms are given in Sect. 6 for structural optimisation problems with design-dependent loads. Finally, Sect. 7 concludes the article.

2. Background

In the literature on continuous topology optimisation, significant effort to solve topology optimisation problems considering design-dependent pressure loads has been in the creation of the loading surface [6]. One finds that several methods exist to achieve this; however, they can primarily be arranged into two groups. The first group seeks to identify a fluid-structure boundary and directly apply the loads onto the finite elements. Hammer and Olhoff [12] suggest the use of Bezier spline functions for the identification of iso-density nodal points to obtain the boundary where the pressure will act. This method was improved upon by Du and Olhoff [13,14]; where a modified technique for finding the density isolines is suggested. Fuchs and Shemesh [15] also used Bezier curves, though they defined control points that are independent of density and are controlled by the optimiser. Recently, Lee and Martins [16] improved upon the method of Du and Olhoff [14]; by removing the need for the predefinition of isoline endpoints. Likewise, Gao and Zhang [17] developed a pressure updating scheme for contact problems with solid weight pressure loading. Finally, Zhang et al. [18] presented a boundary search scheme where the sensitivity of the loading to the element density can be ignored since the loads are determined from real element boundaries, rather than isolines. Alternatively, the second group of methods model the pressure loading with alternative physics or utilise mixed formulations to avoid explicitly defining a loading surface. Chen and Kikuchi [19] used a fictitious thermal loading to simulate the pressure and employed a *dryness coefficient* to identify the fluid and solid regions. Similarly, Zheng et al. [20] introduced a potential function modelled on the electric potential and applied a fictitious electric field. Alternative schemes have also been proposed to find design-dependent pressure loads using density-based methods. Bourdin and Chambolle [21] used a fictitious liquid in a fluid-solid-void topology optimisation. They employed a perimeter penalisation technique to avoid homogenisation of the phases. Sigmund and Clausen [22] modelled the fluid region as an incompressible hydrostatic fluid, introducing an extra design variable for each element. They determined the phase of the region using the two design variables. Similarly, Bruggi and Cinquini [23] proposed a mixed equivalent formulation using another element approximation in order to avoid numerical difficulties due to the incompressible model assumption. Recently, Andreasen and Sigmund [24] extended this method to topology optimisation of FSI problems in saturated poroelastic media. Thus, the literature shows that the classic element density-based topology optimisation algorithms become onerous when dealing with FSI coupled systems.

An alternative branch of topology optimisation, which lends itself to the application of design-dependent pressure loads, is based on discrete methods. One such method, BESO, has developed to the stage where it has been used by industry [25]. The discrete update scheme present in evolutionary methods allows the use of separate modules for the fluid and structural domains with different governing equations. This overcomes a well-studied challenge associated with the classic density-based methods: dealing with moving multiphysics loads and interfaces. Therefore, discrete methods, such as BESO, offer great potential for applications in the areas of multiphysics optimisation. However, they are seldom found in the literature, likely due to their oscillatory convergence [10,26]. Possibly the first application of BESO to design-dependent problems can be found in Ref. [27]. Yang et al. [27] applied evolutionary methods [28] to the design of structures, which included structural downward surface loads. They extend the BESO method to applications in fluid-loaded structural problems. Recently, Picelli et al. [7] extended this method to the application of general movable fluid-structure interfaces with design-dependent pressure loads. Later, Picelli et al. [29] applied this method to topology optimisation problems for frequency maximisation considering acoustic-structure interactions. Most recently, Munk et al. [6] coupled a BESO algorithm to a LBM for the design of micro fluidic mixers with the fluid-structural coupling present. They then extended this method to include multiple objective topology optimisation problems with design-dependent pressure loads [30].

Level-set methods have the advantage that material boundaries are implicitly defined, thus they have also been applied to solve pressure loading problems [31–34]. These methods use boundary points as the design variables, deriving shape sensitivities to predict design changes. However, because the optimisation is based on the structural shape movements, they have been criticised for being dependent on the initial topology [35]. Challis and Guest [36] propose a level-set method for the optimisation of fluid flow. They show that the discrete nature of the optimisation problem leads to significant advantages over density-based topology optimisation algorithms. Furthermore, the no-slip boundary condition can be implemented directly, which is accurate and removes the need for interpolation schemes and continuation methods. This gives notable computational savings, since it only requires flow to be modelled in fluid regions. Topological changes can be incorporated into the level-set method by altering the level-set evolution equation to include topological sensitivity information [37–40]. Zhou and Li [41] apply such methods to the optimisation of steady-state Navier-Stokes fluid flows. They report on the computational expense of