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MULTI-MATERIAL TOPOLOGY OPTIMIZATION OF VISCOELASTICALLY DAMPED STRUCTURES

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Summary The design of high performance instruments often involves the attenuation of poorly damped resonant modes. Current design methods typically rely on informed trial and error based modifications to improve dynamic performance. In this contribution, we present a multi-material topology optimization as an alternative, systematic methodology to design structures with optimized damping characteristics. A parametric, level set-based topology optimization is employed to simultaneously distribute structural and viscoelastic material to optimize the structure's damping characteristics. To model the viscoelastic behavior a complex-valued material modulus is applied. The structural loss factor is determined from the complex-valued eigensolutions and its value is maximized during the optimization. We demonstrate the performance of the optimization by maximizing the damping of a cantilever beam.

INTRODUCTION

In this contribution we address the optimization of components containing both viscoelastic and structural material to achieve optimized damping characteristics. The design of high-performance instruments often involves the attenuation of poorly damped resonant modes, as has been encountered in the design of optomechatronic instruments at the Netherlands Organisation for Applied Scientific Research (TNO) [1]. Current design methods typically start from a baseline design and introduce stiffening or damping reinforcements to modify these modes. Difficulties in predicting the influence of these reinforcements leads to a time-consuming, trial and error based design proces. To overcome this, we propose a multi-material topology optimization routine as a systematic method for the design of these structures.

Multi-material designs containing viscoelastic material are known to provide high structural damping [2]. These type of materials dissipate energy during deformation. To increase the structural damping, we can therefore introduce viscoelastic materials at locations that undergo deformation. Moreover, the geometrical design could be modified to promote deformations in the regions of viscoelastic material. This provides a challenging optimization problem, where to goal is to achieve optimal structural damping: both the location and the geometry of the viscoelastic regions are determined during the optimization. In previous works these two aspects have been investigated separately: by shape optimization of (un)constrained layer damping [3] and by topology optimization of the material distribution within predefined damping configurations [4, 5]. These methods are limited by the initial design configuration of the viscoelastic material.

To overcome these restrictions, we present a multi-material topology optimization routine to simultaneously distribute the viscoelastic and structural material throughout the design to optimize the damping characteristics. The proposed method is able to achieve freeform material distributions, resulting in higher structural damping. Moreover, the method does not require the designer to specify any initial (un)constrained layer configuration for the viscoelastic material.

TOPOLOGY OPTIMIZATION OF VISCOELASTIC AND STRUCTURAL MATERIAL

In this work we aim to optimize the damping characteristics for structures subjected to harmonic excitations. This allows to represent the viscoelastic material behavior using a complex-valued material modulus [6]. Either a complex-valued shear, bulk or Young's modulus can be applied. In the remainder of this work, it is assumed that only shear deformation dissipates energy and therefore a complex-valued shear modulus is implemented. The structural loss factor is applied to quantify the damping of these designs [7]. However, compared to the referred implementation the complete complex-valued eigensolutions are used for the formulation of the structural loss factor to achieve better prediction of the structure's Q-factor.

A multi-material, parametric level set method allows to describe multiple material regions within the design domain [8]. We have opted for a level set-based approach, in order to obtain clearly distinct material regions. Trials using density-based multi-material topology optimization often resulted in designs containing mixture of materials that are difficult to interpret. For each material a level set function is defined, which are parameterized using radial basis functions [9]. The numerical implementation applies four-node square quadrilateral (Q4), plane stress elements to discretize the domain. The material properties of any elements near the boundaries of the level set functions are scaled by the ersatz material model. Also, the discrete Heaviside and its derivative are implemented with continuous approximations. Finally, the Method of Moving Asymptotes (MMA) solves the gradient-based optimization problem [10].

The optimization aims to maximize the structural loss factor corresponding to the specified number of eigenmodes. Constraints are applied to limit the volume of viscoelastic material and enforce a minimum eigenfrequency. An exact formulation

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of the structural loss factor are found by an adjoint sensitivity analysis. The complex-valued eigenvalue problem encountered in the adjoint sensitivity analysis is dealt with similarly as presented in [11].

To illustrate the performance of the optimization routine the maximization of the damping of a cantilever beam is presented. Figure 1a shows the initial design domain with $L = 70$ and $H = 20$ elements. The average damping of the first and second resonant modes is maximized during the optimization. The volume of viscoelastic material is constrained to 40% of the domain volume and a minimum eigenfrequency for the first resonant mode is imposed. The materials have the following properties: structural $E = 200$ GPa, $\nu = 0.3$, $\rho = 7.85 \times 10^3$ kg/m³ and viscoelastic: $E = 1$ GPa, $\nu = 0.3$, $\rho = 1 \times 10^3$ kg/m³ and a material loss factor equal to 1. Figure 1b shows the final converged design after 35 iterations. All constraints are satisfied and an objective value of 0.5057 is obtained. The design shows a freeform distribution of viscoelastic material and achieves higher structural loss factors compared to conventional CLD configurations which vary between 0.26 and 0.39 for the analyzed domain. Since a complex-valued shear modulus was assumed, the dissipated energy is directly related to the shear strains during resonance. Figure 1c and 1d present the shear strain distribution and illustrate that almost all viscoelastic material contributes to the total energy dissipation for the optimized modeshapes.

CONCLUSIONS

A well-performing topology optimization approach has been presented which is able to generate multi-material designs with optimized damping properties. The level-set based formulation provides a clear separation between the different material phases compared with previous investigations using density-based approaches. With the presented example, we have demonstrated that the optimized designs achieve significantly higher structural loss factors compared to conventional constrained layer damping configurations by applying a freeform distributions of the viscoelastic and structural material. This offers new potential for applications where high structural damping is an important design aspect, e.g. high precision equipment and satellite instruments.

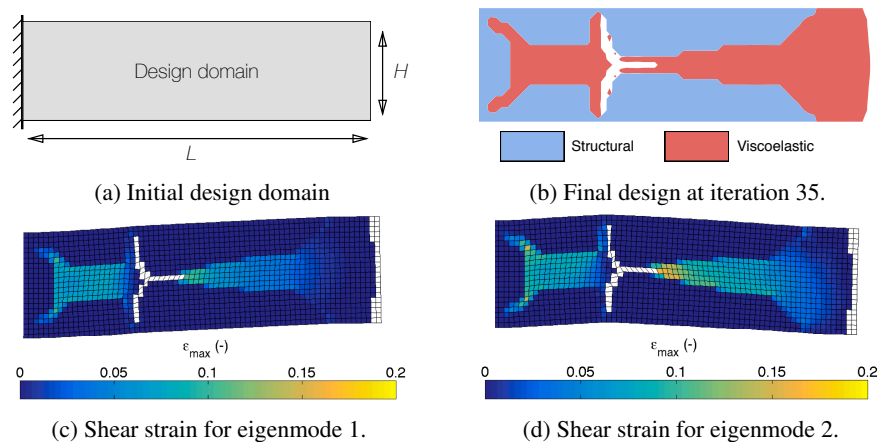


Figure 1: Example of loss factor maximization of a cantilever beam. (a) design domain, (b) obtained distribution of viscoelastic and structural material after 35 iterations, (c) shear strain in first resonant mode and (d) shear strain in second resonant mode.

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