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High-precision motion system design by topology optimization considering additive manufacturing

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Abstract

In the design process of high-precision motion stages, the dynamic behavior is of paramount importance. Manual design of such a stage is a time-consuming process, involving many iterations between engineers responsible for mechanics, dynamics and control. By using topology optimization in combination with additive manufacturing, post-processing using traditional machining and parts assembly, it is possible to arrive at an optimal design in an automated manner. The printing, machining, and assembly steps are incorporated in the optimization in order to directly arrive at a manufacturable design. With a motion stage demonstrator optimized for maximum eigenfrequencies, it is shown that combining additive manufacturing and topology optimization at industry-relevant design precision is within reach and can be applied to high-performance motion systems.

Motion system • Additive manufacturing • Topology optimization • Eigenfrequency

1. Introduction

Dynamic behavior is a key aspect in the design process of high-precision motion stages. The manual design of a stage for optimal relevant eigenfrequencies is a lengthy process, requiring extensive iterations between mechanical designer, the dynamics engineer, and the control engineer.

With the emergence of additive manufacturing, previously unproducible geometries can be fabricated, although the process imposes different manufacturing constraints. The resulting range of design options is so enormous, that manual design approaches are incapable of exploiting the full potential. Through computational design approaches such as topology optimization, design iterations can be performed more swiftly and consistently in an automated process. However, application of topology optimization at the design resolution needed for high-precision motion systems still forms a major computational challenge, next to other crucial aspects such as ensuring printability and the integration of assembled parts into the optimization.

In this contribution, we present an approach to address aforementioned challenges, in the form of a case study with a demonstrator. The demonstrator (Fig. 1a) consists of a magnetically levitated stage, which fulfills the requirements for a vacuum-compatible semiconductor inspection system [1].

2. Method

In the demonstrator (Fig. 1a), the short stroke chuck is to be fabricated by metal additive manufacturing, enabling maximum design freedom for the topology optimization algorithm. Its dimensions are 400x400x48 mm, which is printable by the MetalFAB1 system of Additive Industries in the aluminium alloy AlSi10Mg. After postprocessing by means of traditional machining, actuators and other necessary components can be assembled.

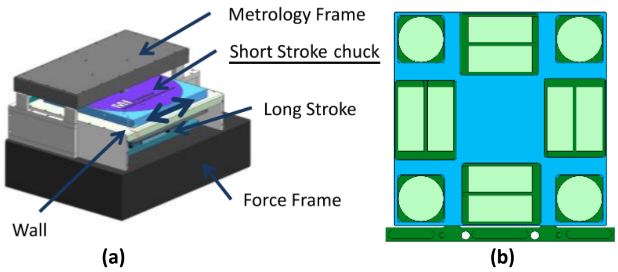


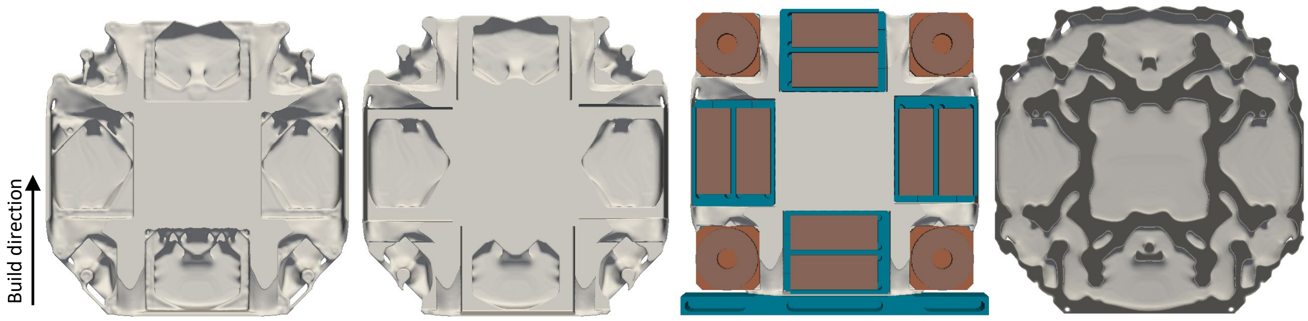
Figure 1. (a) Overview of the magnetically levitated stage as in [1]. (b) Layout of the chuck: the green areas are static components, and the area indicated in blue is the design volume.

2.1. Optimization procedure

The goal of the considered optimization is to maximize the chuck's first three eigenfrequencies ω_i for a given mass M_{lim} of the chuck (Equation 1), which can be attained by optimal material-distribution $\boldsymbol{s}$ in the available design space in between the actuators, as can be seen in Fig. 1b.

$$\begin{aligned} \min_{\boldsymbol{s}} \; & \sum_{i=1}^{3} \frac{1}{\omega_i^2(\boldsymbol{s})} \\ \text{s.t.} \; & \boldsymbol{K}(\boldsymbol{s})\boldsymbol{\phi}_i = \omega_i^2 \boldsymbol{M}(\boldsymbol{s})\boldsymbol{\phi}_i \\ & M(\boldsymbol{s}) \leq M_{\text{lim}} \end{aligned} \tag{1}$$

To enable large scale computations, a structured grid of hexahedral trilinear finite elements with a resolution of 1mm is used. In this way the entire structure is discretized by a mesh consisting of 9 million elements and 28 million degrees of freedom on which the eigenfrequencies need to be solved. Using a parallel implementation, based on PETSc [2,3], and running on 384 processors results in a computation time around 15 minutes per design iteration (the total number of iterations is 100).



(a) Printed final design **(b)** Machined final design **(c)** Assembled final design **(d)** Internal structure

Figure 2. The optimized design at different process steps: (a) the design after additive manufacturing, (b) the design after machining, (c) the final assembled design, and (d) a crossection showing internal structures. The arrow indicates the build direction.

In order to arrive at a practical design, the geometry needs to fulfil requirements on printability (the design needs to be self-supporting) and on structural integrity (all components need to be connected). To achieve this, the simulation inside the optimization is set up in a way to reflect the different stages in the physical production process: additive manufacturing, post-processing, and assembly.

Additive manufacturing. Since a structured grid is used, the overhang filter of Langelaar [4] is used to ensure a 45° overhang angle (Fig. 2a), ensuring a self-supporting geometry. The overhang filter is preceded by a Heaviside filter in a robust formulation [5] in order to gain feature-size control and prevent overflow of sensitivities of the overhang filter.

Post-processing. In the post-processing step, some of the support structures are removed, and pockets are cleared for the actuators (Fig. 2b). A small penalty factor is added to minimize the use of sacrificial support structures. At locations where fasteners (bolts and alignment pins) are positioned, a constraint is added to ensure placement of material.

Assembly. To represent the final assembled structure and its dynamic performance, the geometry of the actuators is projected on the structured grid, with the correct material properties (Fig. 2c). In this way the same regular element grid is not only used to determine printability, but is used again for efficiently solving the eigenfrequencies of the assembled system.

3. Results

After optimization, the optimized stage is obtained without any human interference and within reasonable time: the entire optimization is completed in about 25 hours, just over one day. The printable design (Fig. 2a) is entirely self-supporting with an intricate inner structure (Fig. 2d), which can only be fabricated using additive manufacturing. The use of sacrificial support structures, as seen in Fig. 3, is kept to a minimum by the penalty factor on supports.

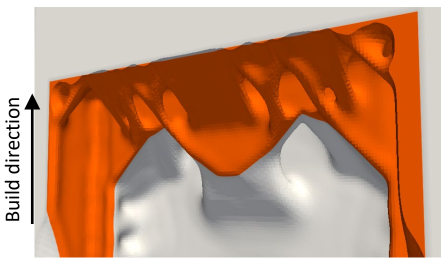


Figure 3. Detail of support structures, where the area to be removed in post-processing is indicated in orange.

From the numerical performance comparison in Table 1, it is clear that the eigenfrequencies of the optimized design (Fig. 2c) are superior compared to either the previous design [1], as seen in Fig. 1a, and a straightforward solid chuck, as seen in Fig. 1b. Note that the mass of the designs has been kept constant, as to use identical magnetic gravity compensation systems [1]. Experimental results can not yet be given, as the demonstrator is currently being manufactured.

Table 1 Comparison between the previous, solid and optimized design

	Unit	Previous [1] (Fig. 1a)	Solid (Fig. 1b)	Optimized (Fig. 2c)
Mode 1 Torsion	Hz	293	340	602
Mode 2 Saddle	Hz	406	402	756
Mode 3 Umbrella	Hz	515	511	864
Dimensions	mm	460x460x35	400x400x31	400x400x48
Mass	kg	7.5	7.5	7.5

4. Conclusion

Combining additive manufacturing and topology optimization enables the systematic and fast design of high-precision motion systems, as demonstrated by the case study presented in this paper. With all the relevant manufacturing considerations, a ready-to-print, high-resolution optimized design was generated in a single day. In terms of dynamic performance, the assembled motion system based on the obtained design outperforms reference designs by a large margin. This proves that the combination of additive manufacturing and topology optimization at industry-relevant resolutions is within reach and provides new opportunities to realize motion systems with superior performance. The demonstrator is currently being fabricated and live demonstrations will be given during the conference.

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