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Complex compliant mechanisms for Fused Filament Fabrication

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Abstract

Additive manufacturing offers the possibility of integrating complex geometries and intersections within one component. This results in the potential to develop innovative compliant mechanisms, which has not yet been fully explored. The use of elastic deformations in compliant mechanisms allows for the transmission of motion or force in a way that is advantageous in comparison to conventional rigid mechanisms due to reduced manufacturing costs, lower maintenance requirements and higher reliability. This paper investigates the potential of Fused Filament Fabrication for the development of novel, intricate compliant mechanism geometries, with a particular focus on mobility. In the course of this investigation, linear flexible mechanisms were evaluated in order to analyse their performance. For this purpose, Finite Element Analysis was used in order to simulate the behaviour of the mechanisms under different loading conditions. Furthermore, the printability of the geometries was analysed using Fused Filament Fabrication. The results show that additive manufacturing provides new opportunities for the development of compliant mechanisms, offering not only new forms of energy absorption but also a promising outlook for the production of these mechanisms.
keywords: Compliant Mechanism, Fused Filament Fabrication, Finite Element Analysis

1 Introduction

Additive manufacturing (AM) enables the production of complex geometries while reducing material waste and manufacturing costs. Among AM techniques, Fused Filament Fabrication (FFF) is recognized for its accessibility and affordability, making it well-suited for prototyping and low-volume production [1, 2]. Compliant mechanisms, which rely on the elastic deformation of flexible members to transfer motion, offer several advantages, including a reduction in part count, simplified assembly, and enhanced reliability [3]. Their application in AM has gained attention for facilitating lightweight, monolithic designs with high precision. However, designing these mechanisms is particularly challenging due to the complex deflections and stress distributions involved [4]. This study investigates the development of linear-motion compliant mechanisms using FFF with Onyx, a nylon polymer filled with micro-carbon fibers. Three designs were evaluated through Finite Element Analysis (FEA) under static and dynamic loading conditions. Experimental results demonstrated the potential of FFF in fabricating functional compliant mechanisms, contributing to the understanding of design optimization and material efficiency.

2 Experimental setup

2.1 Development of the compliant mechanisms

The compliant mechanisms were developed to exhibit a spring-like behavior, enabling linear motion. The development was constrained by a static force of F_{st} = 20 N, a dynamic force of F_{dyn} = 60 N, and dimensions of width b = 50 mm, height h = 100 mm and length L = 100 mm.

Mechanism 1 follows a symmetric leaf spring design, incorporating a combination of corrugated and straight beams. Initial designs revealed high stress concentrations at beam connections, prompting modifications such as smoother transitions and adjustments to beam geometry. These changes improved flexibility and distributed stress more evenly. Mechanism 2 is based on a folded beam structure, refined iteratively using the FACT (Freedom and Constraint Topologies) method to synthesize flexure elements and ensure the desired degrees of freedom. Rounded edges and angled transitions were added to reduce stress concentrations and optimize the transfer of force from the stage to the ground. Mechanism 3 was developed using topology optimization to achieve a structure with high stiffness in all constrained directions while maintaining flexibility for controlled vertical motion.

The design was initially developed as a 2D topology optimized for specific degrees of constraint and freedom, generated using MATLAB, MathWorks, USA code presented by Koppen et al. [5], and was later adapted into a 3D structure. The development process followed an iterative workflow guided by FEA. Adjustments were made to the geometry, beam connections, and dimensions based on simulation results to meet displacement and load-bearing requirements.

2.2 Numerical analysis

The mechanical behavior of the three compliant mechanisms was analyzed using FEA under static and dynamic loading conditions. For the dynamic analysis, an element size of A_e = 3 mm was used to balance computational efficiency and accuracy. The stage displacement along the y-axis, denoted as u_p, was the primary focus, with displacements in other directions being minimal and excluded from the analysis. The dynamic displacement distributions for all mechanisms are shown in Figure 1.

Under static conditions, Mechanism 1 achieved a safety factor of S = 4.3, with stress concentrations observed at beam connections. Mechanism 2 demonstrated a safety factor of S = 3.3, with higher stress localized in the straight beams.

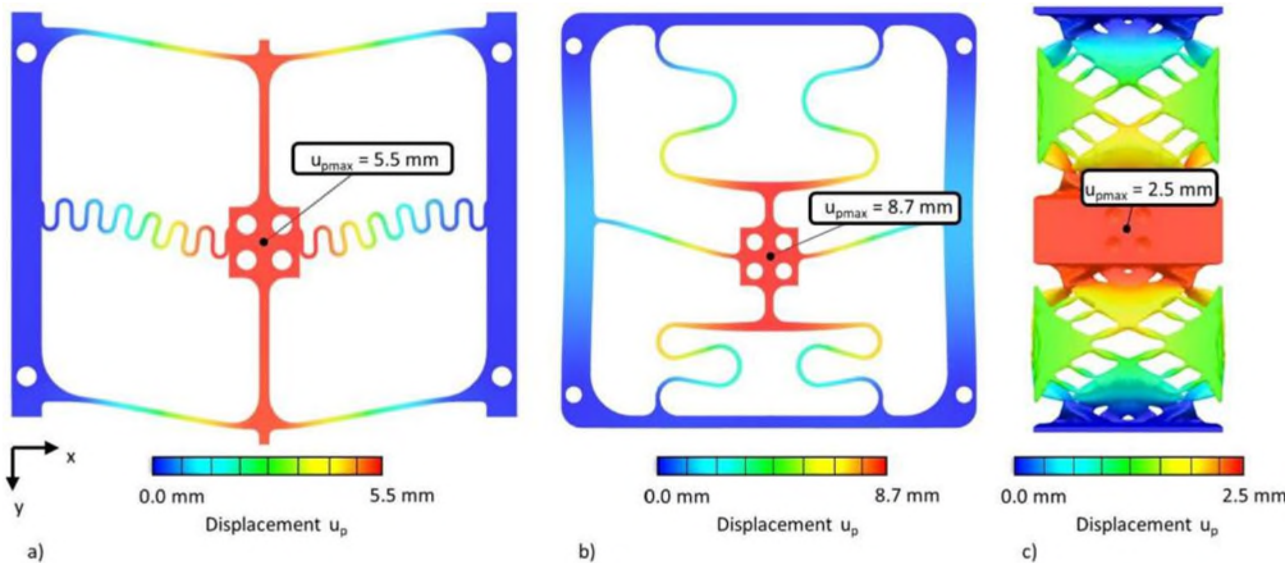

Figure 1 Results of the numerical dynamic analysis showing the displacement u_p; a) Mechanism 1; b) Mechanism 2; c) Mechanism 3

Mechanism 3, developed through topology optimization, exhibited the lowest safety factor of S = 1.6, with stresses concentrated in thin connecting features.

In the dynamic analysis, Mechanism 1 reached a maximum stage displacement of u_p = 5.5 mm, corresponding to a displacement-to-length ratio of δu = 12.8 %. Mechanism 2 displayed the largest displacement, u_p = 8.7 mm, with δu = 24.3 %. Both mechanisms meet the large displacement criterion, defined as exceeding 10 % of the beam length [4]. Mechanism 3 achieved a dynamic displacement of u_p = 2.5 mm, which does not meet this criterion. Due to its high element count, the simulation of Mechanism 3 was conducted on a reduced model utilizing its symmetry plane.

2.3 3D Printing Results

The compliant mechanisms were fabricated using the Onyx Pro 3D printer from Markforged, USA and Onyx material. Mechanisms 1 and 2, both featuring planar designs, were successfully printed without support structures. The chosen orientation effectively addressed challenges associated with thin features, with a thickness of x = 1 mm. Mechanism 1 showed smooth surfaces and well-defined flexures, while Mechanism 2 displayed comparable quality, with minor filament gaps observed at beam connections and transitions. The printed Mechanism 2 is shown in Figure 2.

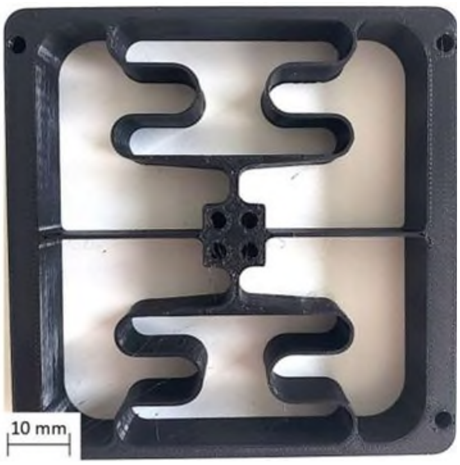

Figure 2 Printing result of Mechanism 2 using FFF

Mechanism 3 required extensive support structures, which damaged internal areas during removal. Printing without supports caused fractures in the thin features, demonstrating the challenges of producing such designs using FFF.

3 Conclusion

The findings of this study demonstrate the feasibility of using FFF for the development and fabrication of compliant mechanisms designed for linear motion. Through an iterative process guided by FEA three mechanisms were developed, analyzed, and fabricated to evaluate their structural performance and manufacturability.

Mechanisms 1 and 2, with planar geometries, met the displacement and load-bearing requirements while maintaining adequate safety factors. These designs were fabricated without support structures, highlighting the capability of FFF to efficiently produce mechanisms with minimal post-processing. Mechanism 2, in particular, achieved the largest dynamic displacement, making it suitable for applications that demand large displacement linear motion. In contrast, Mechanism 3, with its topology-optimized design, revealed limitations inherent to FFF. The extensive support structures required during fabrication led to damage in internal features, and attempts to print without supports resulted in fractures. These findings provide important guidance for the future design and optimization of compliant mechanisms.

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