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A DFAM FRAMEWORK FOR THE DESIGN OF COMPLIANT STRUCTURES

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ABSTRACT

Additive manufacturing methods present prospects for designed mechanical deformation via the integration of controlled anisotropic lattice structure forms. Their assimilation into a Design for Additive Manufacturing (DfAM) process would create a novel framework for the design of compliant mechanisms (CM). The method uses lattice structures to replace rigid multi-part mechanisms, with integrated and controlled flexibility into a single, compact, and precise component. In recent years, a lot of research has gone into making algorithms that enable users to generate CMs for their designs. But by relying on algorithms to design solutions, are they neglecting to fully understand how these mechanisms work. This work undertakes the design and development of a novel DfAM Framework, that utilises controlled lattice structure deformations to create a standardised method of CM design. The authors have developed a method for this, whilst allowing users to tailor CMs to their design, by using a wide selection of pretested structures. Indicating suitable structures for their design using an integrated novel taxonomy. The framework is tested and developed using a series of case studies.

Keywords: Design for Additive Manufacturing (DfAM), Compliant Mechanism Design, Lattice Stuctures, Case study, Intelligent materials

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1 INTRODUCTION

Compliant mechanisms (CMs) transform motion, forces, or energy from input to output. Compared to rigid-body mechanisms, CMs are monolithic and gain at least some mobility from the deflection of flexible members rather than movable joints. This gives CMs the advantages of increased precision and reliability, combined with reduced wear and the lack of need for lubrication. These flexible deformations can be found in lattice structures, yet there is no suitable method for integrating them into mechanisms. ("Compliant Mechanisms Explained", 2022; Howell and Midha, 1995)

In this work, the term "lattice structures" refers to the external form and tessellation of an AM part's geometry. What makes lattices unique is their ability to form ideal structures comprising small architectures with a network of nodes and beams or struts. This format dramatically reduces weight while retaining structural integrity and giving more control over specific qualities. As a result, mechanical performance could be enhanced and use less material without weakening the part, maintaining a high strength-to-weight ratio (Loginov et al., 2019).

1.1 Compliant mechanisms

One thing that makes the traditional design of mechanical components compelling is that designers can separate different functions to be done by different parts, and each part is assigned to do that one function (Howell et al., 2013). The benefit and burden of compliant mechanisms (CM) are that they integrate different functions into fewer parts. As a result, CMs may accomplish intricate tasks with very few parts, but they can be more challenging to design. Understanding how to control the mechanical deformation behaviours of various lattice structures and a database presenting these findings would help simplify this process if integrated into a novel or pre-existing DfAM process (Hossain et al., 2021; Howell et al., 2013; Ion et al., 2016).

1.1.1 Linking mechanical motion to additive manufacturing

In mechanics, there are four basic types of motion: Linear, Oscillation, Reciprocation, and Rotary motion. Each is achieved using different mechanical means that help us understand linear motion and motion control (Donohue and Richards, 2015; "Changing speed - Mechanical devices", 2021). These motions are illustrated and detailed below in Figure 1.

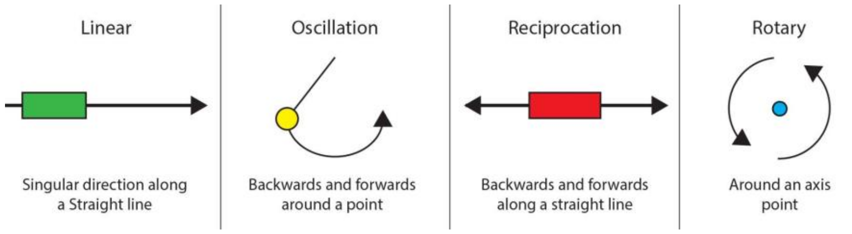
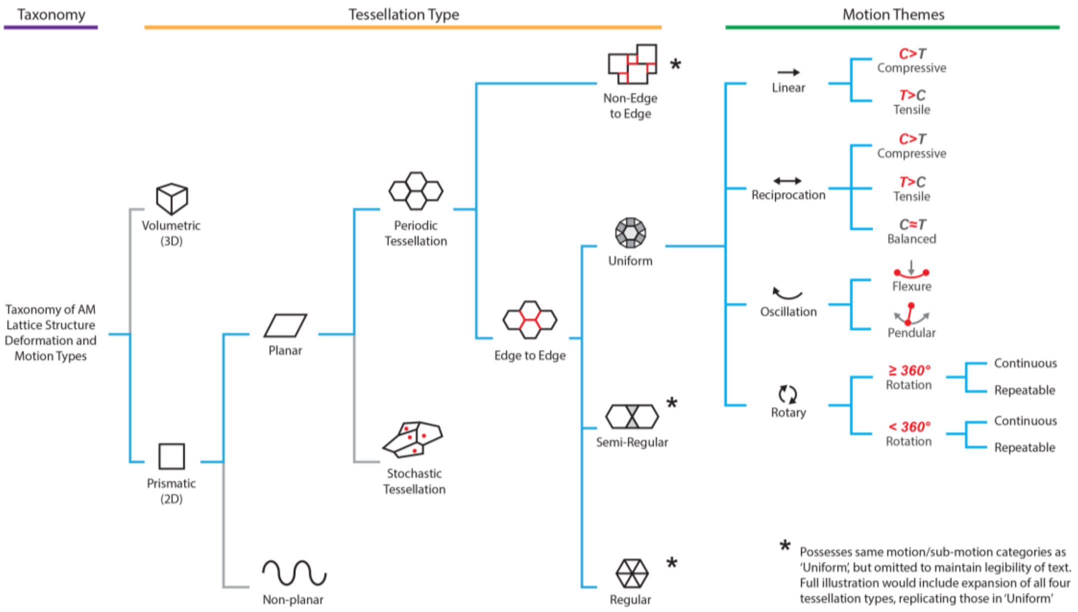


Figure 1. The four basic motion types and their behaviours (Air and Wodehouse, 2023)

Understanding different lattice structure types and predicting their behaviours was crucial to the theory that their deformations can be controlled and predicted (Hossain et al., 2021). Despite not being a usual classification method, these motion types present parallels with the deformation behaviours of lattice structures in AM and thus are suitable to be adopted.

1.1.2 Deformation taxonomy of AM Lattice Structures

In previous work, Air and Wodehouse (2022) developed a novel classification taxonomy for the deformations of additively manufactured lattice structures. The taxonomy linked the predicted deformation mechanical deformation of pre-existing lattice structures to the four basic types of motion in mechanics. A dendrogram of this classification can be seen below in Figure 2.



* Possesses same motion/sub-motion categories as 'Uniform', but omitted to maintain legibility of text. Full illustration would include expansion of all four tessellation types, replicating those in 'Uniform'

Figure 2. Deformation taxonomy dendrogram categorising lattices by tessellation types, motion themes and sub-motion themes (Air and Wodehouse, 2022)

In this dendrogram, two sections represent visual and behavioural elements. The yellow section details the key underlying concepts that describe each structure's tessellation type and how these geometries are arranged and constructed. The green section highlights suitable motion themes for each lattice. In addition, sub-motion themes were created to detail further the types of motions each lattice can achieve. The lattices may be suitable for more than one motion type depending on their experimental results. This helps identify more adaptable samples and does not signal any drawbacks within a sample should it qualify or not for multiple types.

The dendrogram will be used in this work to assist in the redesign of rigid-body mechanisms to CMs, identifying suitable lattice structures that can replicate the motions of the mechanism being redesigned. In addition, the classification will be integrated into a novel DfAM framework, developed to aid the redesign of rigid-body mechanisms as compliant without using complicated algorithms.

1.2 Compliant mechanisms in additive manufacturing

Compliant mechanisms are simple to design and easier to produce. Whereas traditional mechanisms are meticulously designed to eliminate any flexible areas to avoid elastic deformation and, thus, energy have transfer loss, CMs take advantage of elastic deformation to transfer energy or apply force to the intended object. In addition, the low part count of compliant mechanisms compared to ridged-body mechanisms makes them easier to design in a single part. This flexibility in design means that they can be produced using production methods such as additive manufacturing (Howell et al., 2013).

In addition, CMs are also cost-effective and can be more environmentally friendly. Due to their simplistic design and flexible material requirement, CMs can be printed using 3D printers, making them cheap, widely accessible, and easily replaceable. CMs can also be printed using biodegradable materials such as PLA plastics, making them more environmentally sustainable than metal mechanisms, which may also require lubricant oils, damaging the environment.

Additive manufacturing (AM) allows CMs to be produced at a microscopic scale, which is impossible for rigid-body mechanisms due to their complexity. This also increases compliant mechanisms' portability over traditional mechanisms due to generally reduced size and lightweighting properties (Danun et al., 2020; Kiener et al., 2021).

1.3 Design for additive manufacturing

Development of DfAM started with establishing various AM design rules and guidelines based on the possibilities and limitations of AM that arise from the principle of adding material to the workpiece, the type of processed material and the technical capabilities of AM machines (Meisel and Williams, 2015). Therefore, the early research in DfAM focused on determining AM limitations to establish basic design rules and ensure the manufacturability of AM parts. This provided a basis for the development of various design guidelines for DfAM.

1.3.1 *Key principles of DfAM*

The Design for Additive Manufacturing (DfAM) objectives and goals consist of three levels of abstractions of traditional design for manufacturing and assembly (DfMA):

1) Provide tools, techniques, and guidelines for adapting the design with a specific set of final manufacturing constraints.
2) Measure and understand the impact of the design process on the manufacturing system to improve product quality.
3) Determine the relationship between design and manufacturing and its impact on designers and practices (Meisel and Williams, 2015; Rosen, 2014; Lauff et al., 2019; Perez et al., 2015)

From this, we can establish three refined principles that any new DfAM framework will need to include and aid in achieving:

1) Knowledge of AM processes and materials
2) An understanding of DfAM tools (mainly software) and adopting a DfAM mindset
3) An appreciation for the design problems and opportunities suited to AM

Although there's a lot of software today to help users design for AM, they still need to understand the essential differences among the AM processes and technologies – from powder bed fusion to stereolithography to material jetting. Each of these offers different part characteristics and design opportunities (Perez et al., 2015). To design for AM, you must also understand the available materials (polymers, resins, metals, etc.) and their characteristics during and after the 3D printing stage.

Currently, slicer tool software is used for DfAM, taking a CAD digital file and optimising its features for AM. These programs enable engineers to create part iterations, simulate stresses on parts, generate the required support structures for the AM process, and even estimate the cost and time of printing the part based on materials and the available printer (Meisel and Williams, 2015; "DfAM - The Ultimate Guide", 2022).

Topology optimisation and generative design software, often built into the CAD and DfAM software, lets you optimise a component to reduce the required amount of material while maximising its strength and performance. Software assists engineers in making the intricate calculations involved in topology optimisation whilst allowing them to maintain a level of understanding of how it works (DfAM - The Ultimate Guide", 2022; Lauff et al.).

1.3.2 *Key requirements of compliant mechanisms DfAM*

Suppose a DfAM process that aids the design of Compliant mechanisms is to be developed. In that case, it is essential to understand their objectives and requirements and what makes them an improvement on rigid-body mechanisms. There are seven elements to good compliant mechanism design: Part consolidation; Production processes; Cost; Accurate motion, Functionality, Performance, Scale, and Predictability. Combining these factors gives compliant mechanisms a considerable advantage over rigid-body mechanisms (Olsen et al., 2010; "Compliant Mechanisms Explained", 2022) - incorporating them into a DfAM framework will aid in its usefulness and validation.

2 MATERIALS AND CASE STUDY SELECTION

Case studies will be used to test, evaluate, develop, and validate the framework. A pre-existing mechanism was selected and redesigned using the framework before assessing how the framework performed during the process and the output compliant redesign of the mechanism. Based on this analysis, the framework was modified to improve its usability and success. Further case studies will be completed beyond this paper to continue its improved development.

It is important to note that this work focuses on the controlled deformations of the lattice structures applied to the mechanisms to see if they can replicate the mechanical motions of the pre-existing mechanism. It is not focused on the materials. The framework is still in the early phases of development. While materials will undoubtedly play a crucial role in its success, the integration of designed mechanical deformation is key to its novelness and validating its potential for developing CMs. Therefore, the detailed integration of materials will be the next phase of the work.

2.1 Software, equipment and machinery

This research utilises case studies in which a pre-existing mechanism is redesigned as a flexible, compliant structure via a novel DfAM framework developed by the authors. Within the framework is a taxonomy of lattice structure deformations by Air and Wodehouse (2022), previously created by the authors for assimilation into this intended framework. The framework was initially developed based on the key principles of DfAM and key requirements for integrating controlled lattice deformations.

A multi-material FDM machine, the Stratasys F170, was utilised for the redesigned mechanisms' physical prototyping in this study stage. The device is characterised by a layer resolution of up to 0.127 µm, a 254 x 254 x 254 mm build envelope, and a heated enclosure to regulate build temperature ("Stratasys F170", 2022). The material used to print prototypes and test their mechanical deformation was FDM TPU 92A due to its flexible properties. Future studies will test like-for-like materials used for the pre-existing mechanism and suitable printers; however, these early samples are for testing designed mechanical motion deformation. Digital simulations were the focus of the CM's successful redesign for numerical data. However, physical testing is also recommended via visual observations and placement in the intended environment. All CAD models were generated using Solidworks, and the files were transferred to Ansys for digital simulations. These simulations applied directional forces like those in the mechanism's intended environment.

2.2 Selection of pre-existing mechanisms to redesign

Pre-existing mechanisms will be selected based on predetermined criteria, including what mechanical motions they perform, how many variations of mechanical motion it possesses, and their suitability for additive manufacturing. Other factors were also imposed due to restrictions and availability of AM machinery and material (however some users may also have this issue). This involved suitability for the AM machine, size of the print, whether it would need to be rescaled, and whether the wall thickness of any applied lattice structures would be too thin for manufacture on this machine.

It was decided that a single motion mechanism would be selected as the first case study. Then the following case studies would possess multiple motions in a single mechanism, increasing redesign complexity and helping to develop the framework's evolution. All motions will, at some point, be tested. This work discusses the first of these case studies. Further, more complex redesigns will be tested in beyond this paper. Considering this, the following rigid-body mechanism was chosen:

- Case Study 1: Spring Check Valve – utilises a spring and disc to close a valve and prevent fluid reverse flow in pipes. One motion is produced by the spring - Reciprocation Motion. (Ziegler et al, 1990).

To fully develop the framework, future case studies will cover all the basic mechanical motions and sub-motions. However, this work will focus on the initial development stage of the framework. It's worth noting that Case Study 1 is not intended to replace the rigid-body equivalent but prove that the mechanical motion can be replicated using this framework. Yet, the eventual goal of the framework is to replace and outperform rigid-body equivalents once material research is later conducted.

3 FRAMEWORK AND METHOD

3.1 Development of process principles for a new DfAM framework

Section 1.3.1 outlines the current key principles of a DfAM process and the key inputs and outputs. This section assimilates that information into new principles for the DfAM framework being developed in this work, with further considerations for CM design (section 1.3.2).

The framework will focus on the compliant redesign before moving on to the more traditional elements of a DfAM process. These will be the two main sections of the framework, fed and supported by relevant inputs and outputs. There will also be considerations for failed attempts throughout the process. Figure 3 below presents a simplified plan of the new framework stages.

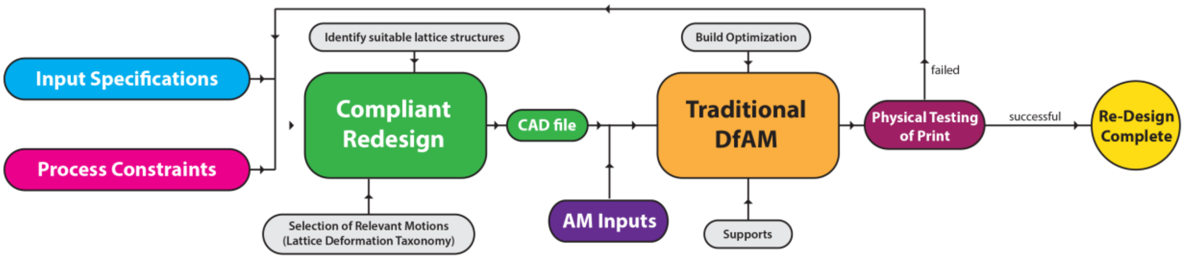


Figure 3. Simplified plan and flow of proposed framework

First, the user will be asked to consider the input data they will need to provide. For example, the numerical forces applied to the mechanism, how many motion areas and types of motions exist, etc. Next, users will be asked questions with yes/no answers throughout the process. The answers provided will allow them to progress or present solutions to resolve issues with their design.

It is also essential to consider the usability and accessibility of the framework for all designers and engineers. Part of this is allowing them to follow the framework using their preferred software for digital prototyping and simulations and not limiting their choices. Users can also choose their preferred equipment and machinery to produce the physical part. The framework will act as a guide in these stages, being more general in its approach.

3.2 Compliant Mechanism DfAM Framework

The simplified framework (fig.3) was augmented in Figure 4 below to add greater detail on the steps involved in each section. It maintains a colour-coded theme of the simplified version, with each section or input being designated a unique colour for better clarity. Within the framework, two main sections represent compliant redesign (green) and traditional DfAM stages (orange).

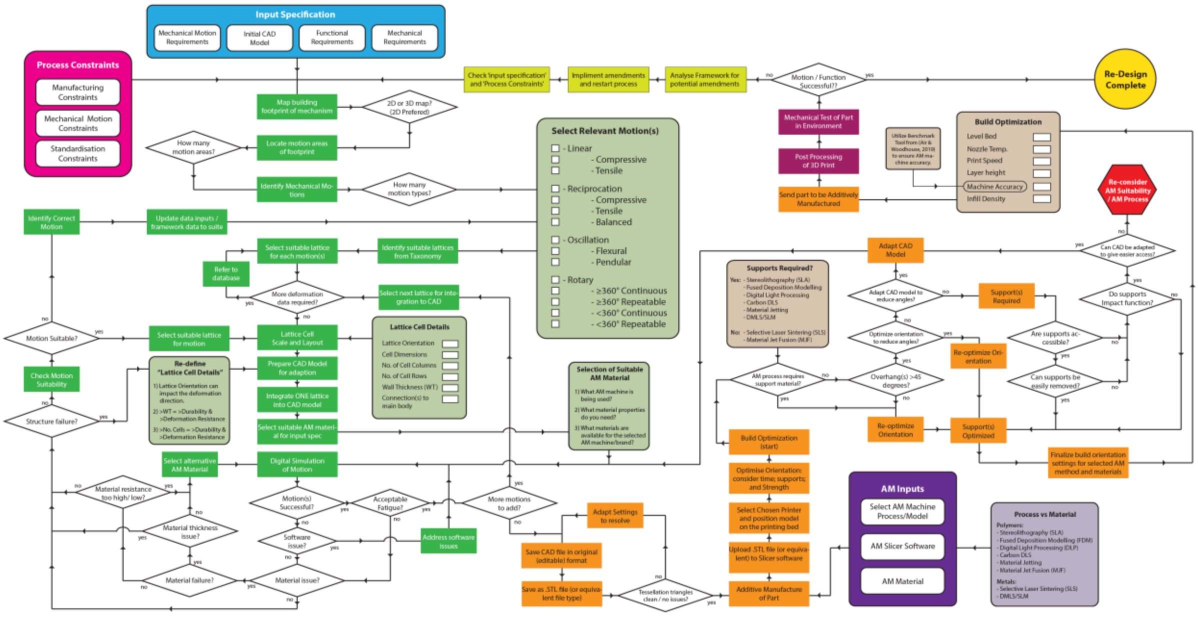


Figure 4. DfAM framework for compliant mechanism design

In Figure 4, the green section details the process for taking a pre-existing mechanism and redesigning it to be compliant via the integration of lattice structures. The information the user provides leads them to a selection of suitable lattices for their needs—the inputs of this section underline Process Constraints (magenta) and Input Specifications (blue). A successful digital simulation of the desired motion(s) within the mechanism sees this section's conclusion and output. Other outputs are the numerical data of the simulations and CAD files for physical prototyping.

The orange section represents the traditional DfAM process, allowing the CM to be additively manufactured. It includes file generation; Process and material selection; Build optimisation; and support structure. The inputs are the CAD models and AM inputs (purple). The output is a physical prototype for mechanical tests. The redesign is complete if the physical testing is successful (burgundy). If it is unsuccessful, there is a loop back to re-analyse the framework for amendments and implementation of those amendments (lime).

4 TESTING & REDESIGN OF A MECHANISM: CASE STUDY

The first pre-existing mechanism to be selected for a compliant redesign was a Spring Check Valve (fig.5) or SCV. The device is operated by fluid pressure, which causes the valve to open, allowing the fluid to flow down the pipe. As a result of any pressure decrease, the spring will begin to push back against the flow and return to its original position, sealing the valve and preventing reverse flow (Ziegler et al, 1990). This motion with the required spring resistance makes the motion type within the taxonomy (fig.1,2) – Compressive Reciprocation.

Figure 5. Spring check valve rigid-body mechanism, with internal spring.

4.1 Compliant redesign section (green)

With compressive reciprocation motion, there is a selection of suitable lattice structures based on previous experiments by the authors. Sinusoidal was deemed the most suitable due to its adaptability and durability. In addition, its arcing beams between nodes provide a predetermined deformation when compressed, and numerical data typically presents reliable elasticity when decompressed.

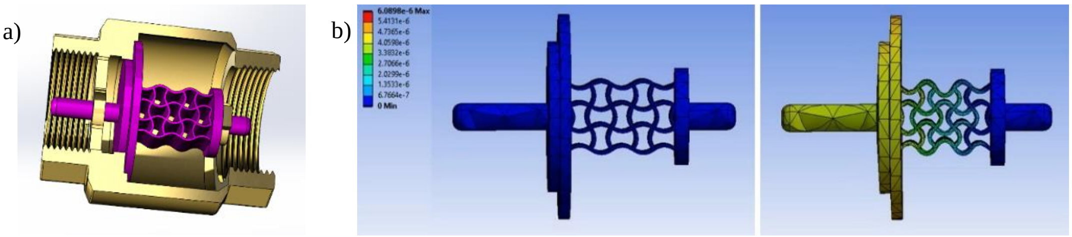


Figure 6. a) SCV compliant redesign CAD; b) Deformation test of SCV redesign in Ansys

A CAD model was developed and designed to incorporate a sinusoidal lattice structure in place of the volume the spring previously inhabited, reducing the number of parts and materials (fig.6a). Next was a simulation of the redesigned mechanism, transferring the CAD file to simulation software. Ansys software was then used to apply 16 bars of pressure to the large plate above the lattice structure. The successful result of this can be seen below in figure 6b. The lattice deformed as required, compressing by 4.9 mm (roughly 25% of its length), enough for a fluid to flow around it. The SCV then returned to its pre-deformation form when the pressure was decreased, halting the fluid flow.

This result concluded the compliant redesign section. However, in further case studies where multiple motions are to be incorporated, the later part of the 'green section' will be repeated until all motions are included in the design and successfully simulated. Users would then progress to the next section.

4.2 Traditional DfAM process section (orange)

After a successful simulation of the motion(s), the framework progresses to a more traditional form of DfAM, where the CAD file in figure 6 is prepared for being physically produced and tested. The framework is intended to be usable with whatever equipment and software are available to the user. The idea is that most printers and CAD, and simulation software can be utilised. Users do not have to be retrained or experts in each medium and use what they already know.

This stage begins with four key inputs: CAD and STL files, an AM machine and material selection, and slicer software. There is an initial focus on the build optimisation of the part via the slicer software - concentrating on supports, orientation, print time, and build strength. Once finalised, the settings of the AM machine are assessed before the part is sent to print and manufactured (fig.7).

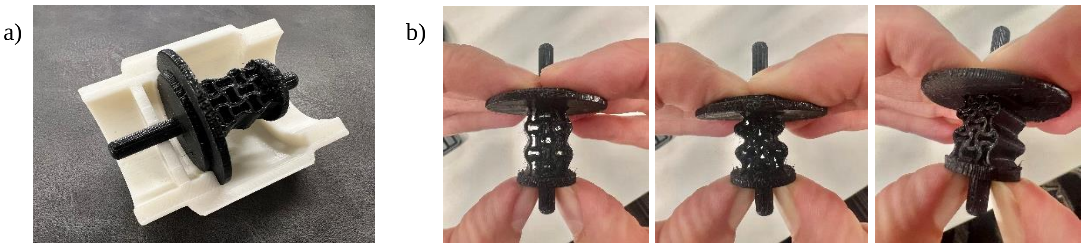


Figure 7. a) Physical prototype of the compliant redesign; b) Physical testing of the part.

Figure 7 above shows a successful print of the redesigned SCV, which concludes the 'orange' section of the framework. This is followed by post-processing of the 3D print and mechanical testing (MT). In this instance, mechanical testing was simulated by hand to analyse the mechanical motion and deformation of the lattice structure (fig.7b). The part performed as expected, compressing by 4.2 mm, with a reciprocation movement and returning to its original form. Compressing by 21% of its 20 mm length is suitable for high-pressure fluid flow, as the Ansys simulation did, at 25% compression. A successful compliant redesign.

5 DISCUSSION

The presented DfAM framework for compliant mechanism design is ongoing research. Thus, the discussion is limited to the theoretical foundations of the process and preliminary validation through the case study. The primary purpose of the method is to incorporate an understanding of how CMs work and how they can improve our product designs through a standardised process that negates the need for algorithms in the early design phases. This is achieved through mapping the key principles of DfAM processes and critical requirements of good CM design and combining them to create a standardised method of CM design.

The case study helped to create a preliminary validation that the framework can be used to create compliant mechanisms that perform desired mechanical deformations. Though, it also helped to highlight areas that can be improved, such as the mechanical testing (MT) phase. Creating a general method for this isn't easy due to the wide variety of potential designs that may be produced using the framework. However, digital simulations should help to bridge this gap. In addition, quantitative data in MT force application and deformation is preferable for measuring a successful motion and function.

Furthermore, an MT of a redesigned mechanism in its intended environment would produce valuable data. The case studies are intended to act as both a validation method and highlight potential issues to be resolved by further iterations. Further case studies will eventually test all potential mechanical motions (fig.2), with some including multiple motions in a single design.

This early stage of the framework's development focuses on the controlled deformations of the lattice structures applied to the mechanisms to see if they can replicate the mechanical motions of the pre-existing mechanism. It is not focused on the materials. The framework is still in the early phases of development. While materials will undoubtedly play a crucial role in its success, the integration of designed mechanical deformation is key to its novelness and validating its potential for developing CMs. Therefore, the detailed integration of materials will be the next phase of the work.

6 CONCLUSION

In this paper, a new DfAM framework for the design of compliant mechanisms is presented. The framework is intended to aid the redesign of rigid-body mechanisms to be compliant by integrating designed mechanical deformation via lattice structures. The proposed framework assimilates the key principles of DfAM and the critical requirements of good CM design. The framework begins by taking a rigid-body mechanism and mapping its mechanical motion area(s) and type(s). Once known, users will select a lattice structure via the author's lattice deformation taxonomy (fig.2) that can replicate each mechanical motion type. The rigid-body mechanism is then redesigned to incorporate the selected lattices into its design and simulated to replicate the intended motion. Once successfully replicated, the framework guides the user through a traditional DfAM process, selecting machinery, materials, and slicer software before optimising the build for manufacture.

The completed print is then subjected to post-processing and physical testing, which must produce similar results to the digital simulations. If successful, the process is completed. If unsuccessful, the framework loops back through the framework to re-assess and look for potential errors and solutions. Users are asked questions with yes/no answers throughout the process. The answers provided will allow them to progress or present solutions to resolve issues with their design. The usability and accessibility of the framework for all designers and engineers are crucial. It is intended to be functional with whatever equipment and software are available to the user. They do not have to be retrained or experts and, in each medium, can use what they already know. The framework will act as a guide in these stages, being more general in its approach. To provide initial testing and development of the framework, a Case Study was presented in which a rigid-body mechanism, a spring check valve, was put through the framework and successfully redesigned as compliant.

To conclude, the main goal of the framework is to standardise CM design. The process offers a structured approach to the design stages and guides the designers through the compliant redesign stage via lattice structures and the traditional DfAM process for manufacturing and testing the redesign. The method should help designers create mechanisms to utilise the unique possibilities of AM and create new and innovative AM products, which will have better functionality and performances compared to the products designed for and manufactured with conventional rigid-body mechanisms. When developed, the framework will benefit new designers by providing a more accessible way of designing CMs suggesting lattice structures for desired mechanical deformations and experienced designers by removing cognitive barriers associated with algorithmic methods.

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