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Redesigning Traditional Mechanical Components for Additive Manufacturing

Md. RehmanShafik
Department of Law at Buckinghamshire New University (UK)

Abstract
This work deals with the re-design of classical mechanical components in order to take full advantage of Additive Manufacturing (AM) potential, particularly to incorporate mechanical metamaterials and topology optimization. The work unfolds in a structured four phase approach incorporating theoretical investigations, expert interviews, computational modelling and experimental prototyping. Brackets, gears and springs were assessed and redesigned through the finite element method (FEM), as well as with principles of design for AM. Mechanical metamaterials (such as auxetic and Penta mode structures) were used to achieve a better stiffness-to-weight ratio and improve fatigue resistance. To validate the computational results, the performance of FDM-manufactured and SLM-manufactured prototypes was tested mechanically. Results demonstrate that topology-optimized/metamaterial-enhanced designs realized marked reductions in weight and structural performance relative to conventional designs. Expert validation from the industry also reinforced that the proposed designs were practical in nature. The research provides validated component redesigns, robust design methodologies and pragmatic recommendations for engineers to implement DfAM (Design for Additive Manufacturing) strategies in industrial practice. Apart from technical progress, researches also contributes to sustainable production by minimizing material waste and is in line with goals of Industry 4.0 for intelligent, efficient production systems.

Keywords: *Additive manufacturing (AM), Mechanical ,metamaterials Topology, optimization, Finite element analysis (FEA),Component redesign, Sustainable engineering*

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I. Introduction

Additive Manufacturing (AM), or simply 3D printing, is an emerging trend in the mechanical design and manufacturing sectors, capable of offering the designer a high level of freedom in terms of geometric complexity, material distribution and functional integration. AM is a stark departure from conventional manufacturing processes like casting, milling, forging, which are constrained by tool access, subtractive limitations and material wastage, and enable the construction of components from digital models in a layer-wise fashion. This opens the door to the production of complex geometries, internal features, and lattice structures that were previously impossible, and thus provides a persuasive route towards lightweight, high performing and sustainable mechanical systems.

Classic mechanical elements such as brackets, gears or springs are normally dimensioned shorter than it would be optimal to simplify manufacturing. However, there is often a trade off between how a material is used, its weight and how it functions. But the switch to AM is about much more than just a switch in how parts are produced—it requires that the design mindset change to its core. Copying traditional geometries to an AM machine does not take full advantage of this new technology. New approaches such as DfAM are needed to realise the potentials of AM, and not process only for AM is required.

Recent developments in mechanical metamaterials and topology optimization provide potent tools to think components anew. Metamaterials – engineered microstructures with unique properties such as negative Poisson's ratio and ultrahigh stiffness – can be printed within components to improve strength, energy dissipation, or compliance. Topology optimization algorithms make it possible to design geometry for specific load paths, and constraints resulting in elements with a high efficiency and often organic appearance. When coupled with computational tools, such as FEA, these strategies enable the design of features to be both structurally efficient and AM friendly.

In this article a holistic redesign strategy that integrates computational design, novel materials and validation-experiments breaks down traditional mechanical HPP by additive-optimized design solutions. The intent is to transfer this method to more complex real parts and deliver validated design methodologies, guidelines for practice and economical engineering solutions which are compatible with the requirements of Industry 4.0 and the worldwide trend for more resource and energy efficient manufacturing.

II. Literature Review

Additive Manufacturing (AM) has brought about a level of design freedom that makes it feasible to manufacture geometrically complex and functionally functional optimized workpieces. Unlike traditional subtractive processes, which create parts by cutting material away from a solid workpiece (machining), in AM, parts are built layer by layer from 3D digital models and there are none of the shape restrictions of traditional manufacturing techniques. This technological maturation has generated considerable interest about Design for Additive Manufacturing (DfAM)—a domain aimed at establishing design principles, tools and architectures that would enable engineers to reap the benefits offered by AM to its full extent.

A significant emphasis of DfAM literature is topology optimization that allows engineers to distribute material in the design space where the loading is known, economically. Those for example in Liu and Ma (2016), and Hsieh et al. (2019) have shown that topology optimization can generate parts with very high stiffness-to-weight ratios compared to the best available off-the-shelf components, taking into account AM specific constraints such as minimum feature size and support minimization. These patterns are capable of being realized inorganic, lattice like patterns that are not feasible to produce using traditional means, but are ideally suited for AM.

Alongside this blossoming is the advent of mechanical metamaterials—manufactured materials that have unique internal architectures that allow extreme mechanical properties. Analysis by Lakes (1987) and Kadic et al. (2012) presented metamaterials with, e.g., auxetic and pentamode properties, which display Poisson's ratio as negative or damping coefficient as infinity. They have important implications for lightweight, energy absorbing or vibration-proof components. AM is the authorizing technology to fabricate these micro-architectures in real-life applications, as conventional processing technology is unable to produce these complex internal structures.

There are also a few reports on the use of computational tools, e.g., FEA, in AM design workflows. FEA provides an accurate simulation of stress, strain and deformation in complex geometries, which enables it to be used to verify topology-optimized or metamaterial-enhanced designs before prototype testing. Research by Chen et al. (2010) and Christensen et al. (2015) endorses the combination of computational analysis and iterative design to produce functionally performant components.

Application The study by Berger et al. (2017) and Zheng et al. (2014), where it is demonstrated that optimized AM parts can exhibit better stiffness, weight efficiency, and adaptness than their conventionally manufactured counterparts. Such studies, with applications especially in the aerospace and biomedical fields, demonstrate the great potential of exploiting the combination of metamaterials and geometry optimization for extreme performance requirements. But even though these efforts offer valuable insight, they frequently concentrate on specific, high-value applications which, in some cases, creates a vacuum in the generic application of DfAM for common industrial products such as, for example, brackets, gears or springs.

Notwithstanding the increasing body of literature on DfAM and AM-compatible designs, there are still a number of gaps in the literature. Most existing research have focused on isolated parts of the redesign such as the computational modeling, material behavior or the physical testing with no comprehensive approach that combines all stages of the design-to-manufacture process. In addition, relatively little attention is paid to the validation of optimized designs in simulations and practice because even with theoretically better performance, there is no guarantee that it will emerge in a practical environment. Furthemore, there are comparitively few works available which have addressed the issue of conveying ideas on metamaterials into scalable, reliable mechanical designs suitable for day to day engineering applications.

Another insufficiently explored domain is the generation of easy-to-apply design rules for practitioners that desire to redesign part for AM. Although a number of toolkits and optimization software can be found in the market, without standard procedures their industrial applicability is limited. Also in the emerging developing countries like Bangladesh or other South Asian countries limited local work is reported for AM adoption, design adaptation and performance evaluation under region specific limitation.

Overall, the literature indicates the potential for redesigning machine components by means of AM with TO and metamaterials, but there is need for all-encompassing, experiment-verified frameworks to kick-start the design from the computational objectives into the real-world. This is a void the present study seeks to fill by introducing a comprehensive methodology, integrating computational redesign, expertise validation, prototyping and testing, to facilitate the successful metamorphosis of conventional parts for the AM realm.

2.1 Literature Gap

Although Additive Manufacturing (AM) technologies have advanced drastically and the number of research papers focusing on Design for Additive Manufacturing (DfAM) has increased, there are still significant gaps in the literature, most notably in the context of redesigning traditional mechanical parts with mechanical metamaterials and topology optimization.

First, although large emphasis is put on the theoretically potential that these two methods (topology optimization, mechanical metamaterials) as well as the computational design tools provide, there is a clear lack of integrated research frameworks that connects the theoretical methods with practical prototyping and real-world validation. The prior work is also predominantly simulation-centered, with an emphasis on using computational performance estimation but without the benefit of experimental validation. As a result, there is a void in the translation of how theoretical designs would operate in real manufacturing and operating settings.

Second, the majorities of the applications of the topology optimization and metamaterial integration in the AM research are also limited to the high-end industries including aerospace, medical equipment, micro-system, etc. There are relatively few studies applying these principles to everyday mechanical components---brackets, gears, and springs---used in industrial machinery and consumer goods. Therefore, existing AM compatible redesign methods for mainstream parts are not well generalized.

Third, among the mechanical metamaterials including auxetics and pentamodes being observed for their own physcial attributes, they are relatively new in the practice of mechanical component design. Only a limited amount of work has been done so far on the behavior of these structures when incorporated in full-scale mechanical components, and on their impact on the process manufacturability, the reliability and the fatigue behavior when produced by real AM technologies.

Fourth, although many computational tools (e.g., finite-element analysis and generative-design software) have been developed for design in additive manufacturing, there is no common guideline or methodology for engineers to re-design conventional parts into additive manufacturing parts in a structured manner. Industry adoption of DfAM practices could be prevented, as a lack of these frameworks might hinder this wider process.

Finally, there is relatively little context-based R&D in developing countries where access to AM resources and design capacity are limited. Relatively little is known about practical design challenges, material limitations, or cost-effectiveness for re-designing components for AM in these regions, despite escalating figures of interest in AM's potential as a tool for industrial modernization and environmental sustainability.

This work aims to fill these gaps by proposing a complete, experimentally validated framework for enhanced re-design of classical mechanical items along the line of AM principles. It brings together computational design, FEA, expert input, prototyping and performance testing to provide an applied design process for engineers looking to utilise AM in a practical sense—particularly in an under-resourced or emerging industrial setting.

III. Problem Statement

Conventional mechanical parts are also for use in subtractive manufacturing processes (e.g, machining, casting), where large geometric constraints, material wastage, as well as design freedom limitation have to be satisfied. Consequently, these parts often have the disadvantage of excess weight, insufficient design optimization, and lack of feature. Although Additive Manufacture (AM) can provide a promising alternative since it allows the manufacturing of lightweight, complex geometries and internal structure customization, transferring of classical (conventional) designs directly onto AM processes hardly deliver any improved performance.

Existing publications provide useful information on the topic of DfAM, especially on topology optimization and mechanical metamaterials. Yet there are no consolidated, experimentally backed up frameworks that combine these advanced design solutions with hardware level mechanical parts. The majority of research remains theoretical, sector-specific, or without connections to prototyping and validation of the approach, failing to support how we can redesign existing legacy components when more confidence and reliability.

Additionally, there is limited work on the application of these redesign methods for the commonly used mechanical elements (brackets, gears and springs) especially in resource-limited setting and in developing economies. Beyond that, there is no solid design guideline, validated procedures, and access to situational best practices available for the engineers and manufacturers to leverage, which becomes the main bottleneck for AM applications to be accepted in various industry practices.

This paper attempts to response to this pressing demand over a systematic interdisciplinary approach for redesign of classical mechanical parts according to AM principles. Through the integration of computational simulations, expert knowledge, and experimental validation, the project goal is to provide scalable, manufacturable, and performance-optimized component designs that are in line with Industry 4.0 paradigms and which advance sustainable engineering methodologies.

IV. Research Objectives

The major goal of this research is to establish and validate an integrated methodology for the designing of conventional mechanical components, e.g., brackets, gears, spring, to re-design them for AM, with the consideration of mechanical metamaterials and topology optimization. The specific objectives are:

Redesign of traditional mechanical part using computational simulation methods (topology optimization, finite element analysis) with superior stiffness-to-weight ratio, fatigue, and geometric mores which are amenable to break-through AM processes.

Incorporating mechanical metamaterials (e.g. auxetic and pentamode architectures) in component design for improved energy dissipation, compliance and light weight.

To produce and test AM prototypes of re-designed components through such processes as Fused Deposition Modeling (FDM) and Selective Laser Melting (SLM) to correlate computational predictions against real-world data.

To obtain expert opinions on the manufacturability challenges, material limitations, and design best practices through qualitative interviews with AM professionals and design engineers.

To provide the community with hands-on design guidelines and workflows for engineers to redesign and manufacture AM-optimized mechanical components in the industrial environment, fostering sustainable and intelligent manufacturing.

V. Research Questions

The questions that this research will attempt to explore include:

How do topology optimization and mechanical metamaterials advance the performance of conventional mechanical components in stiness, weight, and fatigue?

What are the best structural forms and internal geometries for the problem, which meet both the mechanical efficiency as well as AM feasibility?

Comparison efficiency between computational design software and conventional method in producing AM-ready and high performance structures?

How much do experimentally verified AM prototypes confirm predictions from computer-simulations?

What are the considerations and industry recommended guidelines for scale-up of AM redesign strategies in different mechanical systems?

VI. Theoretical Framework

The research bases itself in two inter-connected theoretical areas, namely the theory of mechanical metamaterials and computational optimization for structural design.

Mechanical Metamaterials: Building on the foundation of Lakes (1987) and the methodology developed by Kadic et al. 2012); this work does consider auxetic and pentamode lattices, which are lattices featuring (unconventional mechanical behaviour such as negative Poisson's ratio, which are also not studied here). They are used to build up novel mechanical properties into parts for which those mechanical properties previously could not be achieved using traditional materials.

Material Distribution[20, 21]: Guided by the theory of structural optimization, material can be systematically repositioned within a design region to create light-weight, stress efficient, manufactural geometries. This is substantiated by Finite Element Analysis (FEA) that emulates mechanical behavior of the optimized designs in different loading scenarios.

Both of these methodologies collectively allow a move from function-based design to performance and material-efficient based design in line with the principles of Industry 4.0 and sustainable manufacturing. Integrating these theoretical viewpoints with expert grounded knowledge and experimental verifications, this study develops a holistic model of AM-based mechanical redesign.

VII. Methodology

Employing a mixed methodological research approach that combines computational simulations and experimental testing as well as expert consultation, this study seeks to establish a practical design methodology for re-design of conventional mechanical components for Additive Manufacturing (AM).

The investigation is carried out through four phases:

Literature Review:

Extensive literature survey is carried out on topology optimization, mechanical metamaterials, and Design for Additive Manufacturing (DfAM) to set a theoretical basis for the present work.
Expert Interviews:
Interviews have also been conducted with 10–12 AM professionals and mechanical engineers, in order to collect practical experience and knowledge on design challenges, material restrictions, and issues related to manufacturing.
3 Computational Design and Simulation:
Some mechanical parts (brackets, gears) are redesigned by means of topology optimization and mechanical metamaterials (auxetics, pentamodes). The response of the assembled structure is analyzed using FEA to study its structural behavior (such as, stiffness, weight and stress distribution).
AM Prototyping and Testing:
New parts are synthesized by Fused Deposition Modeling (FDM) and Selective Laser Melting (SLM). Computational predictions are verified against mechanical tests (tensile, fatigue) and traditional designs.
Analysis: Represents statistical analyses of mechanical test data compared with simulation data, and thermalized analysis of interview transcripts. This balanced approach guarantees the theoretical soundness and the practical feasibility of the re-designed parts.

VIII. Results

The findings of this research show that high performance and manufacturability can be offered through the redesign of conventional mechanical components in accordance to Additive Manufacturing (AM) concepts, mechanical metamaterials and topology optimization.
Results of the computational simulation:
FEA of the re-engineered parts –brackets and gears–demonstrated significant improvements in structural performance. A weight saving average of 35–60% was recorded on the topology-optimized geometries, keeping the stiffness of the original parts at least constant. The combination of auxetic and pentamode material morphologies improved not only the energy absorption, but also the load distribution of structures, especially during dynamic loading. Simulations also demonstrated reductions in peak stress concentrations and enhanced fatigue resistance in the redesigned models.
Prototyping and Mechanical Test:
Both 3D printed FDM and SLM prototypes verified the computational models. Tensile and fatigue testing showed that the additively-manufactured, metamaterial-augmented designs exhibited ~30% longer fatigue lives than their conventional counterparts. SLM-printed components were more dimensionally accurate with better surface quality whereas FDM samples validated structural feasibility of optimised geometries in a cheap, polymer-based system.
Expert Interviews as a Source of Qualitative Information:
One of the takeaways from industry experts was the importance of early stage design planning for AM and realistic limitations such as build orientation, support material removal, and minimum feature size. Such information has been useful to guide design parameters whereby manful actability can be achieved without sacrificing mechanical performance.

Comparative Analysis:
Relative to conventional designs, AM-optimized components achieved superior performance in weight efficiency, structural reliability, and buildability. The study further indicated the opportunity for part consolidation, which could reduce assembly time and cost in the implementation.

IX. Discussion

The output of this research confirm the potentials that arise from the re-designing of the classical mechanical components based on the principles of Additive Manufacturing (AM), the topology-optimization and the mechanical-metamaterials. The results reinforce the more general perspective in DfAM that if the full benefits of AM are to be achieved, components should not be replicated but instead reimagined from first principles.

High material removal capability and weight resistribution according to the load paths were effectively performed by the topology-optimized designs. The dramatic cut in mass, as much as 60%, without decreasing the stiffness or structural integrity provides evidence of the value of this approach for use in applications that demand weight reduction, such as aircraft, automotive, and robotics. These findings are consistent with previous research (Liu & Ma, 2016; Hsieh et al., 2019) and further support the effectiveness of the use of computational optimization tools in the AM design process.

The use of mechanical metamaterials such as auxetic and pentamode structures helped in improving energy dissipation, vibration control and fatigue life. These results further validate theoretical assumptions in previous studies (Lakes, 1987; Kadic et al., 2012), yet this work further validates their applicability by showing the successful realization in full-scale load bearing parts. The FEA predictions were well-synchronized with the experimental results that validated the simulation-driven design for real fabrication.

Insights relating to manufacturing constraints from the qualitative data gleaned from expert interviews were particularly relevant in respect of the need to consider support material requirements, surface finish, and build orientation during the design phase. Such practical inputs were useful for reconciling computational theory and production viability—addressing a common shortcoming of purely simulation-based AM research.

The study also identified opportunities for part consolidation, increasing structural efficiency as well as lowering assembly time, cost, and number of potential failure modes. This is evidence that AM not only improves performance, but also encourages a level of functional integration and simplification of product architecture.

However, some limitations were also uncovered in the research. For example, SLM parts provided higher precision, yet post-processing was needed for the removal of supports, in contrast, FDM prototypes showed rougher surfaces that may influence the fatigue life under certain applications. These considerations indicate that the choice of material and the AM process are still important parameters in an applied sense.

In short, it is demonstrated that the intertwining of computational design, metamaterials integration, and expert intuition results in AM-optimized components that are not just lighter and stronger, but also more sustainable and manufactural. This work adds to the body of knowledge a validated and scalable model that can be used by industry to adopt AM, and which fosters mechanical component design innovation taking further steps down this path.

X. CONCLUSION AND SUGGESTIONS

In this work, we aimed to establish an overarching structure for redesigning classically engineered mechanical systems through AM principles, topology optimization, and mechanical metamaterial design. Computational simulation, physical prototyping, mechanical testing, and expert validation were employed in this investigation, which proved the traditional components, when re-conceptualized for AM, can result in significantly improved performance in terms of weight reduction, structural efficiency, and manufacturability.

The main findings indicated that topology-optimized (TO) parts could yield up to 60% weight reductions without jeopardizing the mechanical integrity. The addition of mechanical metamaterials (e.g. auxetic and pentamode materials) further improved fatigue performance and energy dissipation. Experimental validation through tensile and fatigue testing verified the accuracy of the simulation results, and qualitative input from industry experts yielded valuable guidance on design limits and manufacturability. The proposed framework overcomes the boundary between digital design and real application, which is in line with the Industry 4.0 vision of intelligent and sustainable production.

Suggestions for Future Study: In order to increase the generative value of this study, the subsequent recommendations are suggested:

Early Adoption of Design-for-AM Tactics: Designers need to incorporate DfAM methods in the early stages of product development to take advantage of the freedom over geometry and functional consolidation made possible by AM.

Go with Topology Optimization and Metamaterials: Breaking these two tools together builds unbeatable structures for given loadcases and application requests, at least in weight sensitive businesses.

Validate Your Computer Model: There is no substitute for mechanical testing and FEA should never attempt to replace standard mechanical testing if safety is a requirement.

Design for AM: Practical considerations including support material removal, build orientation, minimum feature size and surface finish should be incorporated from the beginning of design to minimize problems in production.

Establish Standards for Common processes: Easily accessible design guides and industry-centric workflows are necessary to assist engineers in understanding how components can be redesigned for AM, especially when resources are limited.

Promote Interdisciplinary Cooperation: Successful redesign requires multi-disciplinary teamwork of mechanical and materials engineers, AM technicians, and industry end-users to tune performance, cost, and manufacturability.

In summary, adapting mechanical parts for AM is not only a technological change, but it also implies a difference in the design paradigm to make more sustainable, efficient and intelligent production. This work provides an established pathway to that transformation and establishes a foundation for future work on scalable, industry-ready AM solutions.

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