On the Dynamics of 3D-printed Gears with Lattice Structure

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Abstract. *The research investigates the integration of different lattice structures into gear design by applying them to the infill zone, which is located between the hub and rim of the gear. 3D models of the gears with varying lattice structures were created, and these gears were then constrained to a shaft for simulation purposes. Using the SolidWorks simulation module, a study was conducted to determine the interactions of natural frequencies, and the results were investigated. Gear variants V1-4 presented a good balance between mass reduction and higher stiffness, displaying higher natural frequencies overall, where these deformations manifest, in comparison to the original structure V0.*

Keyword*s: natural frequency, SolidWorks, lattice structures, additive manufacturing, helical gears.*

1. Introduction

Gears are mechanical parts that use meshing teeth to transfer torque and rotational motion between shafts. Vibrations and noises that accompany their operation are mostly caused by wear, imbalances, misalignments, manufacturing errors, and variations in mesh stiffness [1]. Using lattice structures in the gear body's construction is one method of dampening vibration in gear systems.

The integration of lattice structures into gear design marks a significant advancement in mechanical engineering, fuelled by progress in additive manufacturing (AM) and topology optimization. This literature review explores the evolution, design principles, manufacturing methods, and performance characteristics of lattice-structured gears. The review shows that lattice-bodied gears have progressed from conceptual studies driven by topology to experimental demonstrators made possible by AM. Additionally, there is an increasing theoretical understanding of lattice topology, mechanics, and data-driven performance prediction, which informs optimization strategies and applications in the aerospace and automotive sectors.

Traditional gear design has typically focused on mechanical strength and durability [2], often at the expense of increased weight from solid metal structures. However, the advent of additive manufacturing technologies and advanced computational design methods has created new opportunities for producing lightweight, high-performance gears by incorporating lattice structures. These lattice structures, known for their periodic cellular designs, provide exceptional strength-to-weight ratios and can be customized to meet specific mechanical requirements, all while significantly reducing material usage [3].

The concept of lattice-structured gears combines several technological advances: topology optimization algorithms that identify the optimal distribution of materials, additive manufacturing processes that can create complex internal geometries, and advanced computational methods for predicting and optimizing lattice performance. This interdisciplinary approach has led to the development of gear systems that challenge conventional design paradigms and provide new solutions for weight-sensitive applications in aerospace, automotive, and other industries [4].

The use of topology optimization in gear design gained significant attention around 2018, when researchers developed workflows that treated the gear body as a design domain while keeping the geometries of the teeth and hub fixed during the optimization process. This approach acknowledged that while gear teeth must adhere to precise geometric tolerances for proper meshing, there are considerable opportunities for material reduction and structural optimization in the gear body [5].

Ramadani et al. conducted early research on topology optimization for gear bodies, establishing a foundational methodology for the development of lattice gears. These initial studies primarily aimed to reduce mass and minimize vibration through strategic material removal, thereby paving the way for more advanced lattice-based approaches.

The transition from conceptual topology optimization to practical lattice implementation become possible by advancements in additive manufacturing, particularly in selective laser melting (SLM) technology. Subsequent research led to the development of cellular lattice gears produced through SLM and other additive manufacturing methods. These gears have been experimentally shown to achieve measurable reductions in mass and changes in vibration and strain behaviour compared to traditional spur gears [6], [7].

The experimental demonstrations played a vital role in validating computational predictions and uncovering the practical challenges of manufacturing complex lattice structures. This work highlighted significant discrepancies between idealized computational models and the actual components produced, emphasizing the need to consider manufacturing constraints during the design process.

As lattice manufacturing technologies have matured, several comprehensive reviews and surveys have consolidated knowledge on classification schemes, additive manufacturing (AM)-based design methods, and performance metrics that are ready

for application in lattice structures. This phase of consolidation has been crucial for promoting wider adoption across various industrial sectors and for establishing standardized approaches to the design of lattice gear [6-8].

Recent advancements have led to the development of parametric plate lattices and shape-optimized plate families, which broaden the range of achievable mechanical properties. These sophisticated lattice configurations can be designed to display either isotropic or anisotropic stiffness characteristics, allowing the lattices to approach the theoretical stiffness limits for a given density.

The flexibility of parametric lattice families allows designers to customize gear body properties according to specific loading conditions and operational requirements. This capability is especially valuable in applications where directional loading or specific vibration characteristics are critical design factors [9], [10].

Research on fused filament fabrication (FFF) of polymer lattice structures has yielded valuable insights into the relationships between manufacturing parameters and mechanical properties. Compression tests conducted on FFF-printed gyroid, diamond, and octet lattices have demonstrated that factors such as cell size, strut/wall thickness, and layer thickness significantly influence strength and deformation capacity [10].

Although polymer lattices may not be ideal for high-load gear applications, the insights gained from polymer studies have enhanced the understanding of manufacturing-property relationships that apply more broadly to lattice manufacturing processes [11]. This study serves as an extension of our team's prior research efforts [12], [13].

2. Materials and Methods

Lattice structures are systematically categorized based on their topology and deformation mechanisms, which significantly influence their mechanical behaviour. The main topological classifications include strut-based lattices, surface or shell lattices, hollow-strut configurations, triply periodic minimal surfaces (TPMS) like gyroid structures, and plate lattices [8], [9]. Each class of topology displays unique mechanical properties that make them suitable for various applications.

A helical gear (V0) with the relevant geometrical details shown in Table 1 was used as the basis of the initial design, while the lattice structures (infill patterns) were set in four distinctive designs (V1-V4).

The helical gear's crown and hub were effectively designed with a 100% solid infill, focusing modifications specifically on the region between diameters Ø45 mm and Ø130 mm. Utilizing SolidWorks, all geometries were crafted with direct modelling techniques and standard features, such as Extruded Boss/Base and Circular Pattern, across various iterations, except for the initial version (V0).

Table 1. Relevant parameters of the base helical gear design.

Parameters	Symbol [m.u.]	Value
Gear module	m_n [mm]	2
Teeth number	z	75
Gear width	b [mm]	17
Helix angle	β [°]	10
Pressure angle	α [°]	20
Profile shift coefficient	x	-0.659
Tip diameter	d_a [mm]	153.496
Reference diameter	d [mm]	152.314
Root diameter	d_f [mm]	144.078
Gear Hub distance	d_h [mm]	45
Gear rim distance	d_r [mm]	130
Material	C45-EN 10083-2	

The first variant (V1- Figure 1) was developed by initially sketching a rib and then applying a circular pattern multiplication. The rib thickness was selected at 0.8 mm, whereas the number of multiplication instances is 72, at a total angle of 360°.

a.   b.
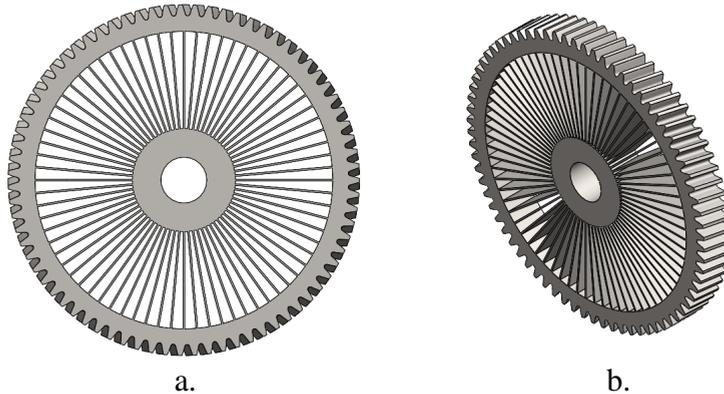
Figure 1. V1 gear model with linear pattern infill (a. front view; b. isometric view)

The second variant (V2- Figure 2) was developed by positioning two circle arcs with an equal radius of R60 at a 45° from the line of reference. Employing the circular pattern multiplication feature, the infill pattern was obtained. The rib thickness was selected at 0.8 mm whereas the number of instances multiplicated was 72 at a total angle of 360°.
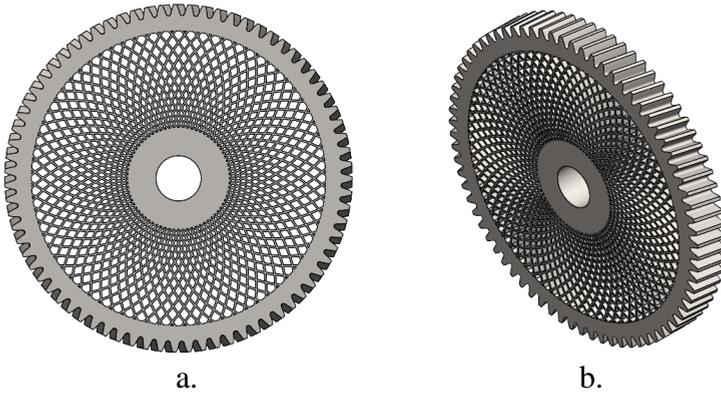
Figure 2. V2 gear model with circular arc pattern infill
(a. front view; b. isometric view)

For the third variant (V3-Figure 3), 0.8 mm thick rib was established, where the chords intersect at 45°. By applying the circular pattern multiplication feature, the infill pattern was created. The number of instances multiplied was 72, with a total angle of 360°.
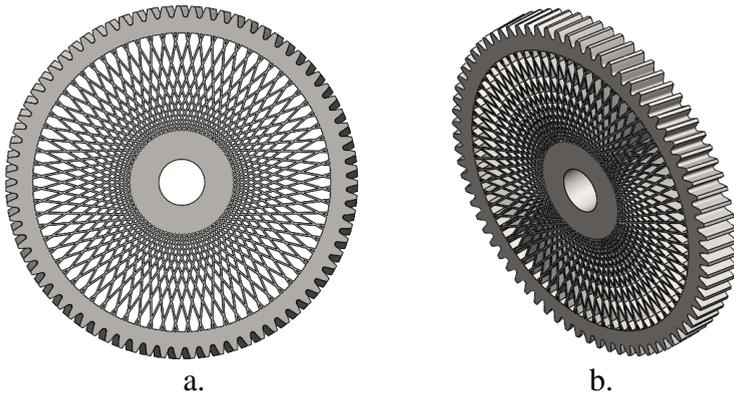

Figure 3. V3 gear model with 45°-line intersection infill
(a. front view; b. isometric view)

The fourth variant (V4-Figure 4) features a honeycomb infill design, consisting of regular hexagonal cells. The wall thickness of these cells is 0.8 mm, and the diameter of the circle inscribed within each hexagon measures 3 mm. The infill pattern was created by applying a circular pattern multiplication feature following the initial sketch. The number of instances multiplied was 72 with a 360° total angle.

a.   b.
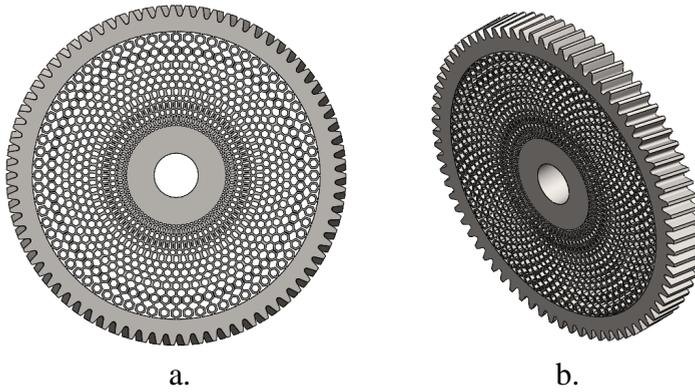
Figure 4. V4 gear model with honeycomb pattern infill
(a. front view; b. isometric view)

For the assessment of the five geometries presented above, finite element analysis and simulations were performed using the Frequency Analysis module, available in the SolidWorks 2024 software [14]. This approach provides valuable insights into the performance characteristics and design optimization of the gears.
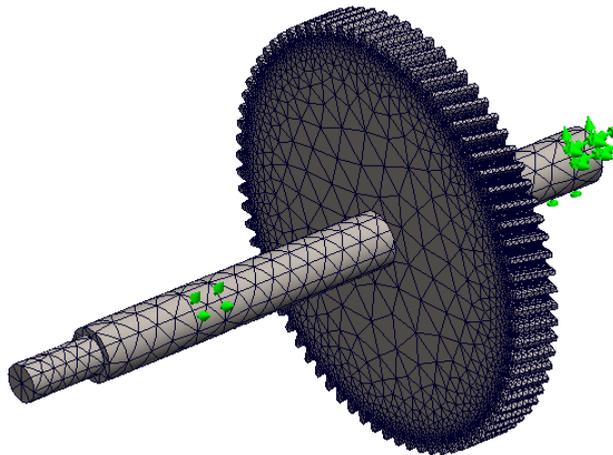
Figure 5. Boundary conditions and the mesh applied in the frequency analysis

The natural frequency analysis for the five geometries was conducted on the helical gear–shaft assembly (Figure 5). The gear wheels were fixed on the shafts by means of press fit. Moreover, appropriate bearing constraints were applied to the shaft.

Table 2. Mesh parameters of the V0-4 gear design.

Details	V0	V1	V2	V3	V4
Mesh type	Solid Mesh				
Mesher used	Blended curvature-based mesh				
Jacobian points for High quality mesh	16				
Max. element size [mm]	14.2549	16.008	19.5354	18.9333	19.6357
Min. element size [mm]	0.719224	0.8004	0.976768	0.946667	0.981785
Maximum Aspect Ratio	5.4613	68.218	85.814	125.97	274.89
Total Nodes	250344	191562	236162	210320	277828
Total Elements	166459	120585	140782	125768	156022

The details regarding the mesh parameters applied to the five gear designs (V0-V4) are presented in Table 2, where the Jacobian points value of 16 indicate fewer sharp edges and/or curved extremities for the generated meshes.

3. Results and Discussion

Table 3 illustrates the variations in mass for the analysed gears. All four lattice structure geometries demonstrate significant mass decreases Notably, the most substantial mass reduction was observed in the V1 and V3 geometries when compared to the original geometry (V0).

Table 3. Variations of the mass for the V0-V4 gear models.

Model code	Mass of the gear (g)	Variation of mass versus V0 model (%)
V0	2266.44	0.00
V1	1041.91	-54.03
V2	1398.08	-38.31
V3	1329.37	-41.35
V4	1397.24	-38.35

Whereas in Figure 6, we can observe the variation of mass through a visual representation of these values.
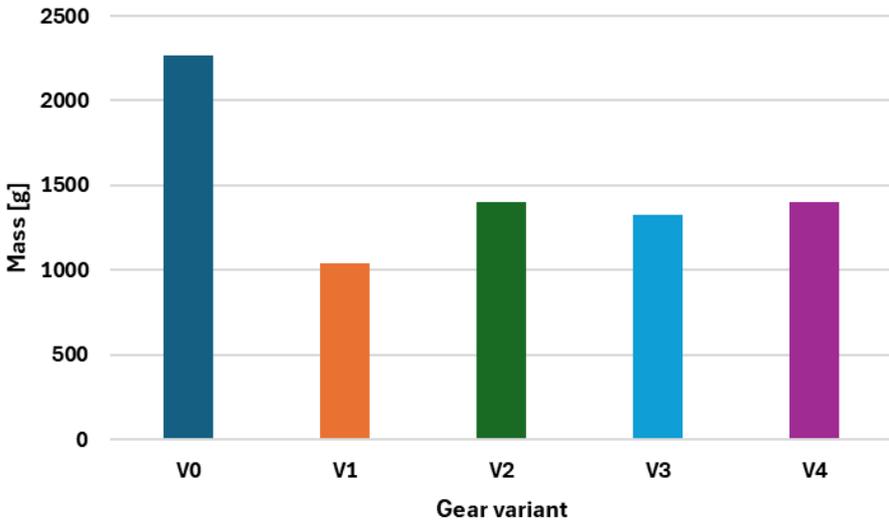
Figure 6. Visual representation of mass variation for the V0-V4 gear models

Table 4 displays the natural frequencies for the first six vibration modes of the analysed geometries, highlighting the effect of geometric modifications on vibrational behaviour.

**Table 4.** Natural frequency comparison between the five models.

Model code	Natural frequencies [Hz]					
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
V0	283.17	912.44	913.15	1166.50	1169.10	2227.40
V1	173.45	1196.80	1198.20	1443.90	1445.70	1773.70
V2	348.74	1113.50	1114.50	1374.60	1375.30	2184.40
V3	357.71	1139.80	1140.30	1399.40	1401.20	2217.70
V4	344.06	1106.90	1108.60	1353.80	1355.10	2187.80

Notably, there are significant differences between the original and modified geometries, as shown in Figure 7, where the modified versions show higher overall frequency values. This trend is directly linked to increased structural stiffness; stiffer configurations resist deformation more effectively, resulting in higher natural vibration frequencies.
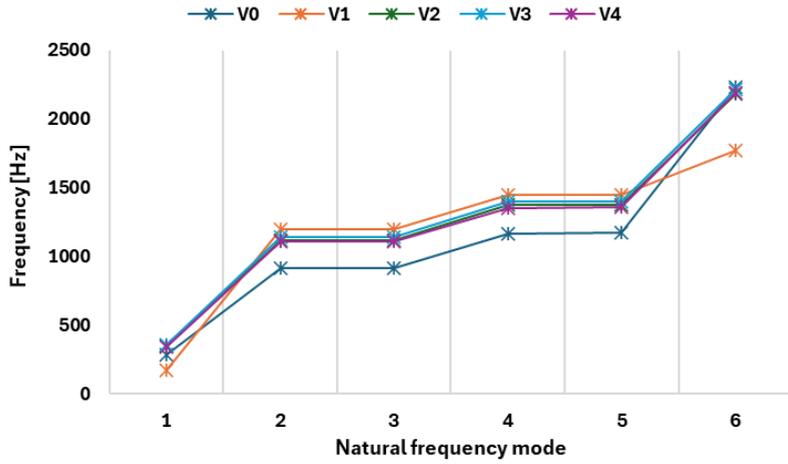
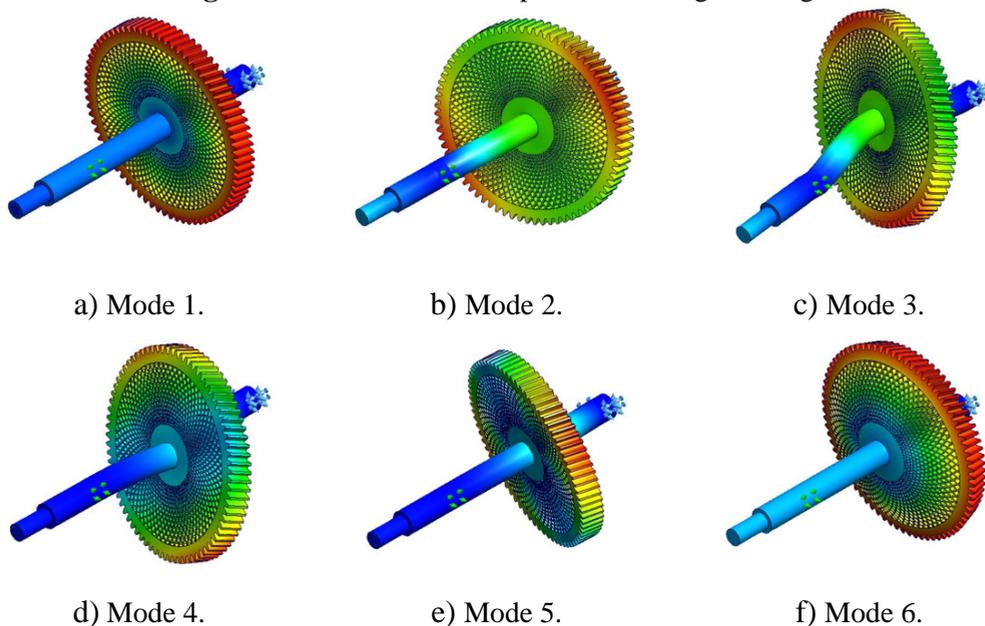**Figure 7.** Visual comparison between the five models

Figures 8-12 illustrate the shapes associated with the first six vibration modes for the gear variants V0–V4. These mode shapes reveal that geometries with lattice infill structures (V1–V4) exhibit similar deformation patterns, indicating a consistent vibrational response due to their periodic lattice architecture.
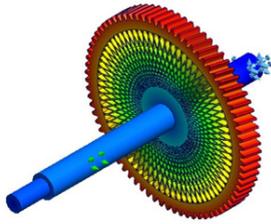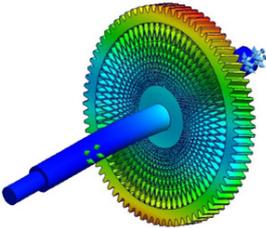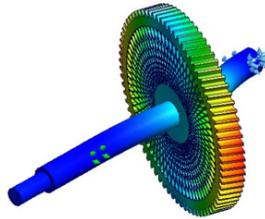

a) Mode 1.

b) Mode 2.

c) Mode 3.

d) Mode 4.
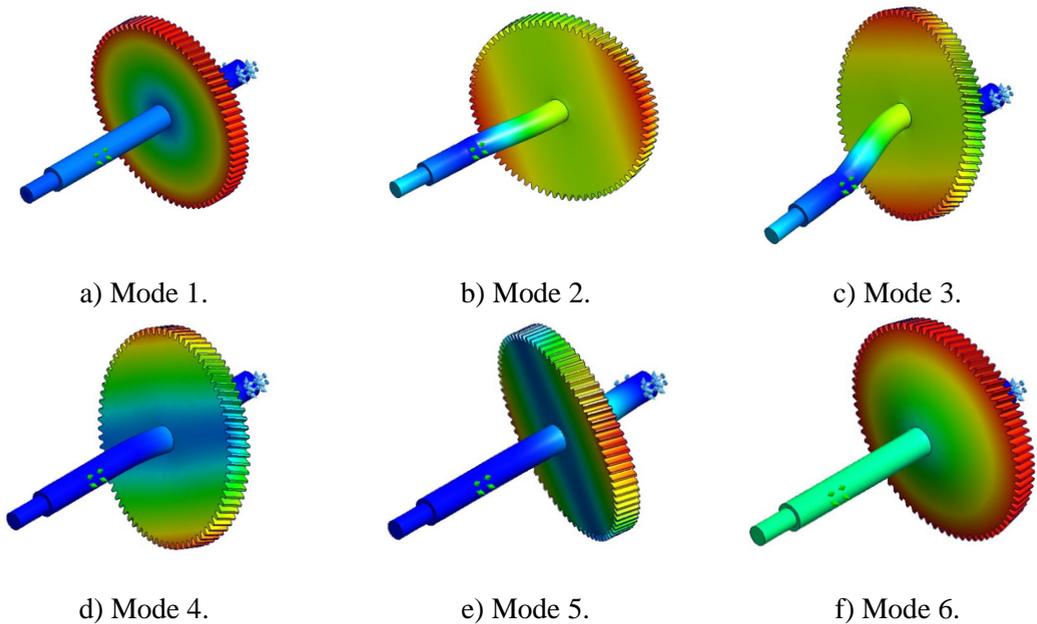
e) Mode 5.

f) Mode 6.

Figure 8. First six mode shapes for the V0 gear design

a) Mode 1.

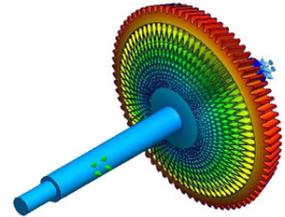b) Mode 2.

c) Mode 3.

d) Mode 4.
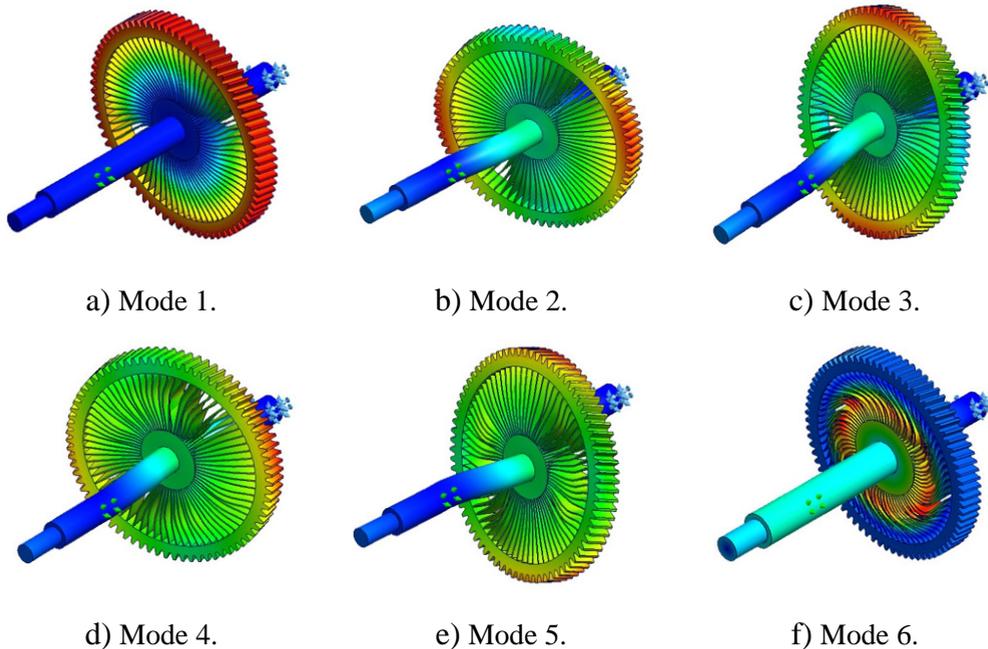
e) Mode 5.

f) Mode 6.

Figure 9. First six mode shapes for the V1 gear design

a) Mode 1.

b) Mode 2.

c) Mode 3.

d) Mode 4.

e) Mode 5.

f) Mode 6.

Figure 10. First six mode shapes for the V2 gear design

a) Mode 1.   b) Mode 2.   c) Mode 3.
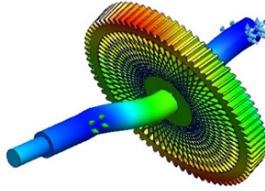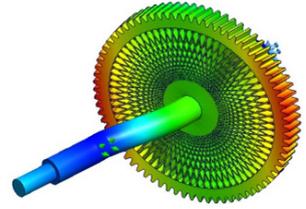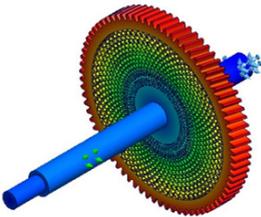
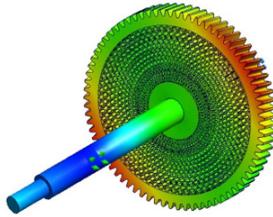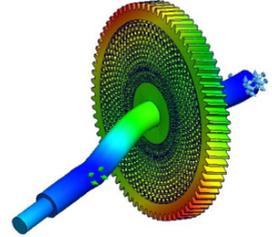d) Mode 4.   e) Mode 5.   f) Mode 6.

Figure 11. First six mode shapes for the V3 gear design

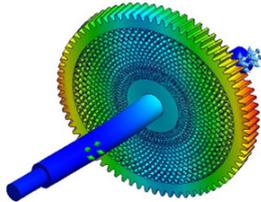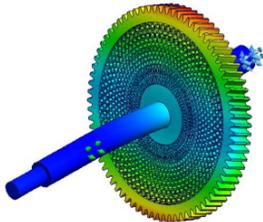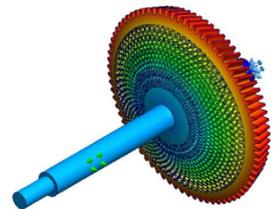a) Mode 1.   b) Mode 2.   c) Mode 3.

d) Mode 4.   e) Mode 5.   f) Mode 6.

Figure 12. First six mode shapes for the V4 gear design

51

In contrast, as it can be observed in Table 4, the original geometry (V0) displays distinct deformation patterns, highlighting the impact of internal structure on vibrational behaviour.

The much lower value of the eigenfrequency corresponding to the vibration mode 1 obtained in the V1 variant, compared to the V2-V4 designs, is explained by the fact that vibration mode 1 is a purely torsional one and V1 is the lattice structure that gives the lowest torsional rigidity. As in modes 2 and 3, bending vibrations are predominant, the deviation of the natural frequencies proper to the 4 variants of lattice structures is much smaller.

The use of optimized infill patterns in the internal structure of additively manufactured helical gears offers the possibility of improving stiffness and increasing natural frequencies while reducing gear mass.

4. Conclusion

The research aimed to investigate the impact of various lattice infill designs on gear stiffness and their effects on total gear mass.

The natural frequencies of the first six vibration modes for the analysed geometries highlight how geometric modifications influence vibrational behaviour. The modified versions exhibited higher overall frequency values, which is directly linked to increased structural stiffness, as stiffer configurations are better at resisting deformation.

Incorporating lattice infill patterns in the internal structure of additively manufactured helical gears not only enhances their stiffness but also increases the natural frequencies at which deformations begin to occur, all while significantly reducing the overall mass of the gears. The findings suggest that using lattice infills in gear design results in favourable stiffness-to-mass ratios.

Overall, this study builds on previous research in the field, laying the foundation for future improvements and optimizations. Future research directions aim to investigate more complex cellular structures, capable of providing both an increased torsional rigidity and to serve as vibration absorber for the gear dynamics.

References

1 Korka Z.I., Vela I., Design and execution of a test rig for studying the vibrations of a gearbox, *Annals of "Eftimie Murgu" University from Resita*, 15(1), 2008, pp. 131-140.
2 Korka, Z. I., Cojocaru, V., Miclosina, C. O., Modal-based design optimisation of a gear box housing, *Romanian Journal of Acoustics and Vibration*, 16(1), 2019, pp. 58-65.

3   Ramadani, R., Pal, S., Belšak, A., et al., *Selective Laser Melting of a Ti-6Al-4V Lattice-Structure Gear: Design, Topology Optimization, and Experimental Validation*, Applied Sciences, 15(14), 2025, 7949.

4   Li, Y., Jiang, D., Zhao, R., et al., *High Mechanical Performance of Lattice Structures Fabricated by Additive Manufacturing*, Superalloys, 14(10), 2024, 1165.

5   Ramadani, R., Belšak, A., Kegl, M., et al., *Topology Optimization Based Design of Lightweight and Low Vibration Gear Bodies*, International Journal of Simulation Modelling, 17(1), 2018, 92-104.

6   Sur, A., & Darvekar, S., *Recent Advancements of Micro-Lattice Structures: Application, Manufacturing Methods, Mechanical Properties, Topologies and Challenges*, Arabian Journal for Science and Engineering, 2021, 46, 8513-8556.

7   *Topology optimization and additive manufacturing in producing lightweight and low vibration gear body*, International Journal of Advanced Manufacturing Technology, 2021, 115, 1639-1651.

8   Yang, S., Dai, N., & Cao, Q., *The Data-Driven Performance Prediction of Lattice Structures: The State-of-the-Art in Properties, Future Trends, and Challenges*, Aerospace, 12(5), 2025, 390.

9   Lu, L., 2023, Parametric plate lattices: *Modeling and optimization of plate lattices with superior mechanical properties*, Additive Manufacturing, 71, 103626.

10 Sharpe, C., & Seepersad, C. C., *Lattice Structure Optimization With Orientation-Dependent Material Properties*, Proceedings of the ASME International Design Engineering Technical Conferences, 2020.

11 Kara, H., & Uzun, M., *Farklı Dolgu Geometrilerine Sahip Dişli Çarklarda Ağırlığın Optimize Edilmesi*, Türk Doğa ve Fen Dergisi, 13(4), 2024, 180-190.

12 Cojocaru, V.; Frunzaverde, D.; Miclosina, C.-O. *On the Behavior of Honeycomb, Grid and Triangular PLA Structures under Symmetric and Asymmetric Bending.* Micromachines 2023, 14, 120.

13 Cojocaru, V., Miclosina C.O. & Korka Z.I., *Study of the dynamic behavior of gears with lattice structure body,* The 3rd International Conference on Mechanical System Dynamics, Sept 23rd– 27th, 2025, Cluj-Napoca, Romania.

14 Dassault Systems, Support Documentation, available online at: https://www.3ds.com/support/documentation/

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