Electromagnetic Modeling of Lattice Structures in Additively Manufactured Electric Machines

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***Abstract*—Recent advancements in metal additive manufacturing (AM) show great potential to revolutionize the design and manufacturing of electromagnetic components used in the field of electrical engineering. Lattice structures directly printed by AM processes typically offer better structural performance with reduced weight, such as high stiffness, surface area, elongation, energy absorption, and porosity, than the solid counterpart. This paper aims to study the electromagnetic modeling of lattice structures used in additively manufactured magnetic cores or windings for electric machines. Three dimensional (3D) electromagnetic finite element (FE) analysis with high performance computing (HPC) shows the highest fidelity in predicting the electromagnetic performance of designs with lattice structures by preserving complex geometry details. FE-based homogenization methods have also been explored to potentially speed up concept design. A case study based on an additively manufactured axial-flux permanent magnet machine with a Hilbert pattern stator validates the discussed electromagnetic modeling approaches.**

***Index Terms*—Additive manufacturing, electromagnetics, electric machine, finite element method, lattice structure, Hilbert pattern**

I. Introduction

Additive manufacturing (AM) enables realizing components with complex geometric shapes which otherwise cannot be manufactured conventionally. This has made it an area of active research interest both in the industry and academia to fabricate unconventionally shaped components for high-performance electric machines [1], [2]. Literature has reported the use of metal AM to fabricate coils with high fill factors, low AC losses, and improved thermal performance [3], [4], permanent magnets [5], and soft-magnetic flux-carrying components such as stators [6] and rotors [7]. These components nearly always have unconventional geometric shapes.

The flux-carrying components in conventional electric machines are made out of lamination stacks to reduce the losses due to induced eddy currents. However, since stacked laminations are discontinuous and require insulation between adjacent laminates, they are infeasible to be additively manufactured. Recent literature has proposed using complex geometries such as the Hilbert space filling curve [8] and the triple periodic minimal surface (TPMS) lattice structure [9] to emulate laminations. A similar approach has been adopted to minimize AC losses in AM windings in [4]. In addition, the use of topology optimization in conjunction with AM, to develop electric machine components with unconventional geometries has also been reported [10], [11].

Nearly all electric machine design workflows involve multi-physics analysis and simulations using finite element (FE) models. However, the complex lattice structures such as the Hilbert and TPMS used in additively manufactured electric machine components introduce challenges with FE modeling, making it difficult to accurately assess the impact of using these components on electric machine performance, without experimental evaluations.

This paper is the first work to systematically study the electromagnetic modeling of lattice structures used in additively manufactured electric machine components, specifically, stator / rotor cores and windings for electric machines. The primary contributions of this paper include:

- Reviewing typical lattice structures used in engineering designs fabricated by AM and their design considerations.
- Providing the electromagnetic performance comparison of two representative lattice structures – gyroids and Hilbert pattern – based on detailed electromagnetic FE analysis of material samples and high performance computing (HPC).
- Proposing FE-based homogenization for material properties of lattice structures to speed up simulations of whole electromagnetic devices, such as electric machines.

It is organized as follows. Section II reviews typically lattice structures used in AM. Section III studies the electromagnetic performance of lattice structures described by equivalent magnetic and loss characteristics, followed by the proposed FE-based homogenization method for lattice materials. Section V reports the comparison between homogenization method and detailed FE method using HPC based on an AFPM motor with an additively manufactured Hilbert pattern stator. Section VI concludes the full paper.

II. Lattice Structures in Additive Manufacturing

Lattice structures, or alternatively known as architectured cellular structures, are meso-level repeated patterns that fill a

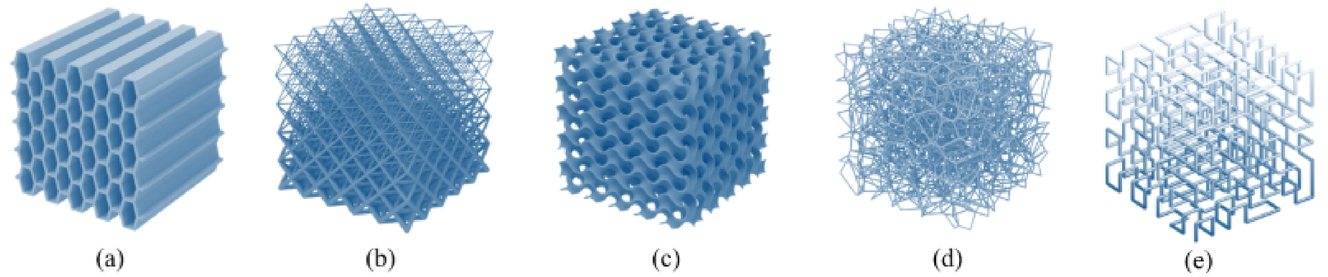


Fig. 1. Typical lattice structures. (a) Honeycomb lattice, (b) Beam lattice, (c) TPMS lattice (gyroid), (d) Stochastic lattice (Voronoi), (e) 3D Hilbert curve.

volume or conform to a surface. In engineering applications, they may be comprised of beams, surfaces, or plates that fit together following an ordered or stochastic pattern to achieve lightweight designs.

The unit cell is the most basic repeating structure of a lattice and it defines the type of the lattice. To increase a lattice, unit cells are arranged in space using a cell map, which can be rectangular, cylindrical, spherical, or even warped to conform between two faces. The lattice properties (electromagnetic, structural, thermal, acoustic, etc.) are determined by the lattice type and other design parameters, such as the unit cell size and the thickness of the beams or surfaces.

There is a vast variety of lattice structures and several ways to create lattices. AM technology, based on a layer-by-layer process from computer-aided design (CAD) models, allows one to directly print lattice structures with high flexibility, reduced processing time and minimal material waste compared to conventional processes [12].

Typical lattice structures are illustrated in Fig. 1. The honeycomb lattice shown in Fig. 1(a) offers high stiffness in a specific direction. Gyroids shown in Fig. 1(c) have a high strength-to-weight ratio and naturally separate the flow into multiple interweaving channels or domains while providing a substantial surface-to-volume ratio, leading to higher efficiency for thermal management and compact heat exchanging applications. Two-dimensional (2D) Hilbert space filling curves have been used in additively manufactured magnetic cores to limit eddy current losses [6], [8].

III. Electromagnetic Performance of Lattice Structures

Lattice structures in additively manufactured magnetic cores change the magnetic permeability characterized by B-H curves, or B-H loops if hysteresis is included, and core losses characterized by B-P curves.

Detailed 3D magnetostatic and eddy current FE analyses on cube samples of the same size (9mm×9mm×9mm) were conducted to study the magnetic performance and loss performance, respectively, which are also dependent on the cube orientation. The cube samples were placed in a uniform external magnetic field along the X, Y and Z directions, respectively. Simulations were run in a powerful workstation with 5 tasks for frequency sweep and 4 CPU cores per task. The second-order Hilbert pattern and gyroid structure has reached 225,936 and 1,297,159 2nd-order tetrahedra, respectively, due to the complex geometry shapes.

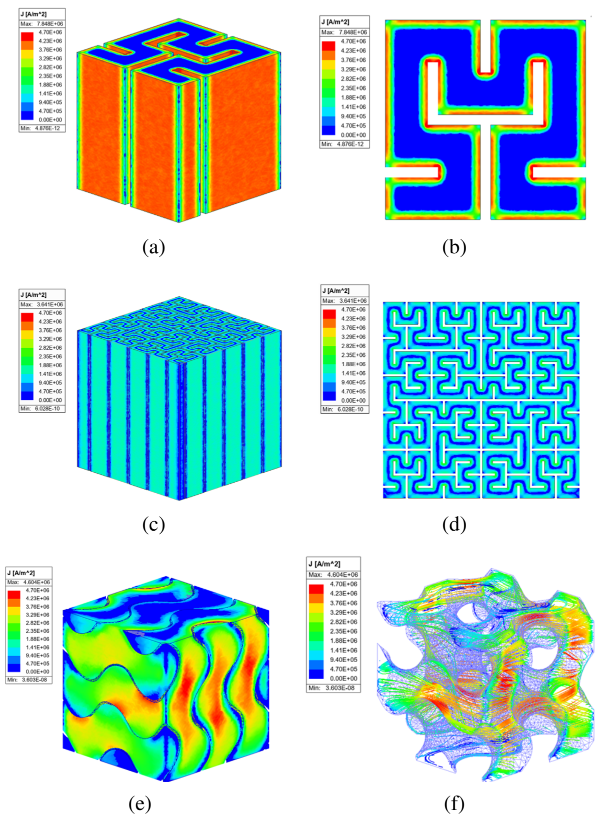


Fig. 2. Eddy current density distributions predicted by 3D eddy current FE analysis at 1kHz based on parameterized cube samples. (a) Magnitude on a second-order Hilbert pattern cube, (b) top view of (a), (c) magnitude on a fourth-order Hilbert pattern cube, (d) top view of (c), (e) magnitude on a gyroid cube, (f) streamline in the gyroid cube.

As shown in Fig. 2, the Hilbert pattern structure enforces the induced eddy current to flow along the Hilbert curve in cross-sectional planes. The fourth-order Hilbert pattern cube has much lower current densities than the second-order one due to a longer eddy current flowing path. Similarly, the gyroid structure only allows the induced eddy current to flow in extended 3D path due to special geometrical connections. As a result, the overall eddy current losses for both cases are much lower than the solid counterpart.

IV. FE-based Homogenization for Lattice Materials

As shown in Section III, the accurate modeling of electromagnetic parts with lattice structures can be time-consuming and generally require HPC due to the geometry complexity. Homogenization is a widely used technique to find the effective, or homogeneous, material properties of lattice structures or composite materials to simplify numerical simulations. In the literature, homogeneous material properties are also known as effective properties, equivalent properties, and average properties.

Homogenization has been seen in modeling materials for electromagnetic components, such as lamination stacks [13], Litz wires [14], and high-temperature superconducting (HTS) coils [15]. For example, in lamination stacks used as magnetic cores for electric machines and power transformers, permeabilities in the lamination plane and in the normal direction have been modified in FE models based on simplified magnetic circuit analysis, as follows:

$$\mu_{eq} = \begin{cases} k_{st}\mu_{iron} + (1-k_{st})\mu_0 & \text{in plane} \\ [k_{st}\frac{1}{\mu_{iron}} + (1-k_{st})\frac{1}{\mu_0}]^{-1} & \text{in normal direction.} \end{cases} \quad (1)$$

where k_{st} is the stacking factor, μ_{iron} the permeability of electrical steel and μ_0 the vacuum permeability.

In most cases, the current in a slot can also be homogenized in such a way that the total current in the coil is correct but the current density in the slot is slightly lower than the actual current density in the copper [13] and a slot filling factor has been widely used to account for this difference.

Based on the underlying formulation, homogenization can be achieved by analytical or numerical methods. In the FE-based homogenization, representative volume elements or repeating unit cells of the heterogeneous material can be modeled with appropriate boundary conditions to obtain the effective material properties. Considering the geometry complexity of most lattice structures, FE-based homogenization is more recommended.

Taking a simple material structure composed of equally-spaced copper cubes as an example. When placed in a uniform magnetic field, each cube of the tested material will have the same electric field $\vec{E}$ (or current density $\vec{J}$) and magnetic field $\vec{H}$ (or flux density $\vec{B}$) distributions, so the material property can be obtained by analzing one repeating unit cell, i.e., one cube placed in the uniform magnetic field.

It has been clearly shown in Fig. 3 that the field distributions obtained from the model with the minimal geometry – one cube – are identical to those from the model with 27 cubes modeled. The tangential H field boundary condition has been assigned to four lateral faces and the zero tangential H field boundary condition to two bases to achieve the uniform external magnetic field [16].

The equivalent material properties obtained from FE analyses of a repeating unit cell can then be used in models of whole electromagnetic devices, such as electric machines. Fig.

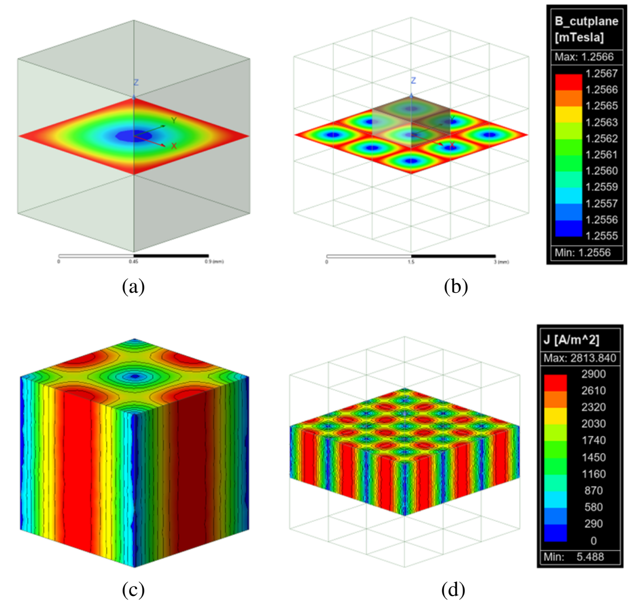


Fig. 3. Comparison between 1-cube and 27-cube models. (a) Flux density distribution from the 1-cube model, (b) flux density distribution from the model with 3X3X3 cubes, (c) current density distribution from the 1-cube model, (d) current density distribution from the model with 3X3X3 cubes.

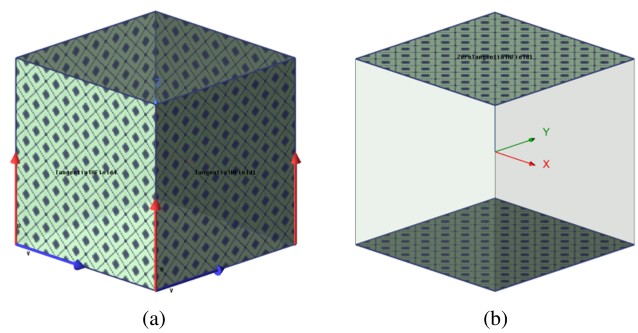
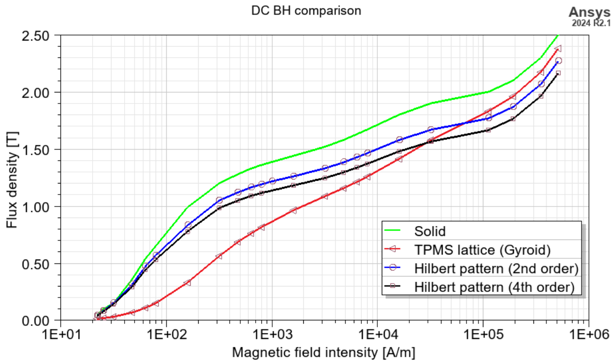


Fig. 4. Boundary conditions applied to one repeating unit cell. (a) Tangential H field on all the lateral sides. (b) Zero tangential H field on the two bases.

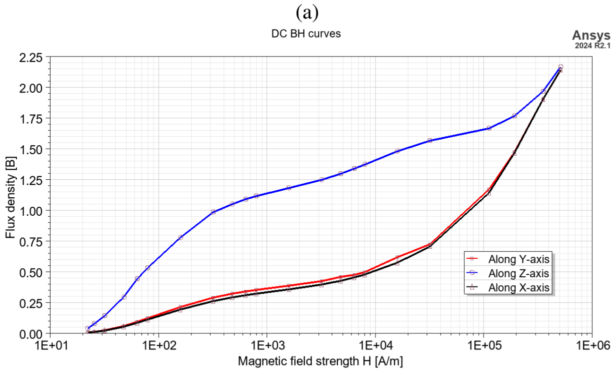
5 shows the equivalent DC B-H curve and eddy current loss per kilogram for two representative lattice structures.

V. Case Study – Additively Manufactured Hilbert Pattern Stator

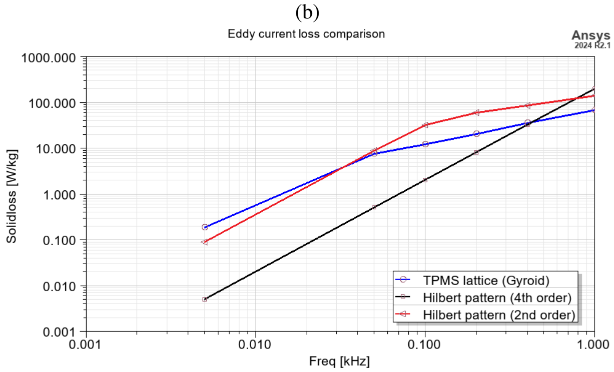
The FE-based homogenization presented in Section IV will be used to simulate the AFPM machine with an additively manufactured Hilbert pattern stator described in [6]. The construction of the studied machine and relevant parameters are shown in Fig. 6 and Table I, respectively. Results from the detailed 3D magnetic transient FE model solved by HPC are shown in Fig. 7 and Fig. 8. By considering the eddy current reaction from the Hilbert pattern stator, the electromagnetic torque is reduced. With a higher rotor speed and operating frequency, the stator eddy current loss increase and the electromagnetic torque reduces monotonically as expected.



(a)



(b)



(c)

Fig. 5. FE-based homogenization for the second-order Hilbert pattern and gyroid structures. (a) DC B-H curves along +Z direction for different structures, (b) DC B-H curves along three directions for the 4th-order Hilbert pattern structure, (c) eddy current loss density at 1kHz for different structures. The gyroid structure shows a higher saturation magnetic flux density than the second-order Hilbert pattern structure but generally lower permeability. The second-order Hilbert pattern structure produces more eddy current loss when the frequency is higher than 40Hz for the 9mm×9mm×9mm cube sample. With a higher order of Hilbert pattern, the eddy current loss will be lower.

TABLE I: Parameters of the studied AFPM machine with an additively manufactured Hilbert pattern stator.

Parameter	Value
Number of pole pairs/stator slots	8/24
Number of turns in series per phase	56
Stator inner/outer diameter [mm]	71.5/82.3
PM thickness/airgap length [mm]	5.3/2.0
Tooth axial length/slot width (parallel slot) [mm]	23.0/8.0
Stator/rotor yoke thickness [mm]	12.0/6.5
Rated current [Apk]	140
Max. speed [rpm]	6,000

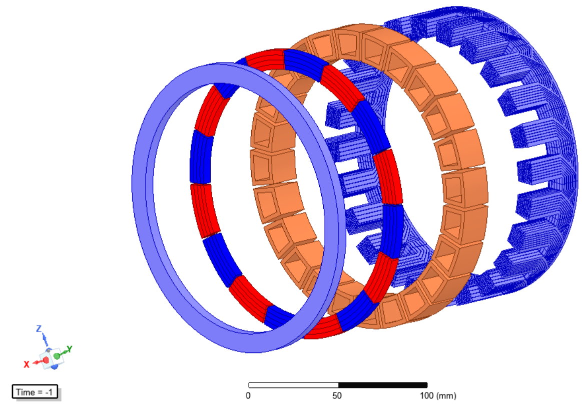


Fig. 6. Construction of the studied additively manufacured Hilbert pattern stator AFPM machine.

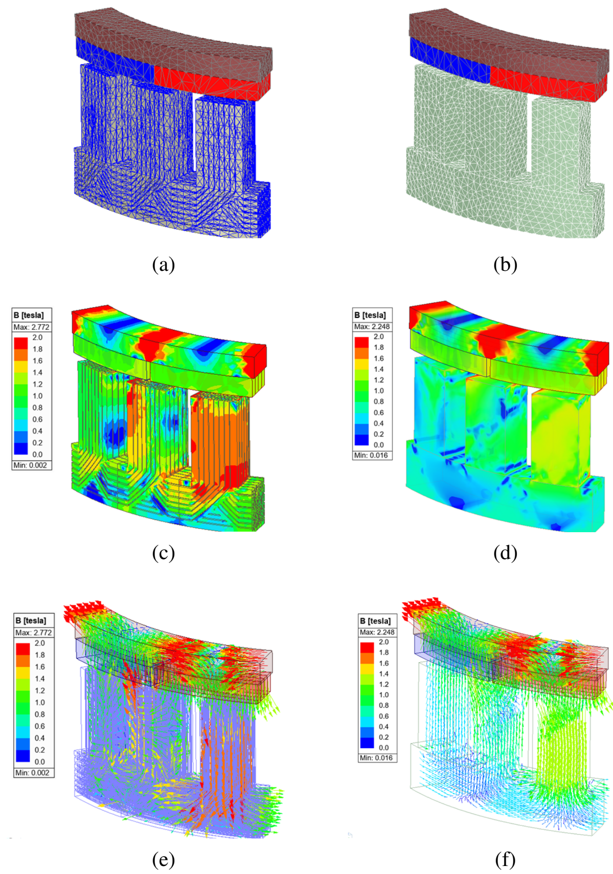


Fig. 7. FE modeling of the additively manufactured AFPM machine with a detailed Hilbert pattern stator geometry. (a) Mesh plot for the detailed model, (b) mesh plot for the homogenized model, (c) flux density magnitude for the detailed model, (d) flux density magnitude for the homogenized model, (e) flux density vector for the detailed model, (f) flux density vector for the homogenized model. The magnetic transient FE model has 482,911 second-order tetrahedra and has been solved in 2hr 11min in a powerful workstation using 18 CPU cores for the detailed model. One eighth of the full machine has been modeled and only one coil is shown for clarity. The homogenization method reduces the computation time by more than 10 times. The DC B-H curves used in tooth and yoke portions of the homogenized model are from Fig. 5.

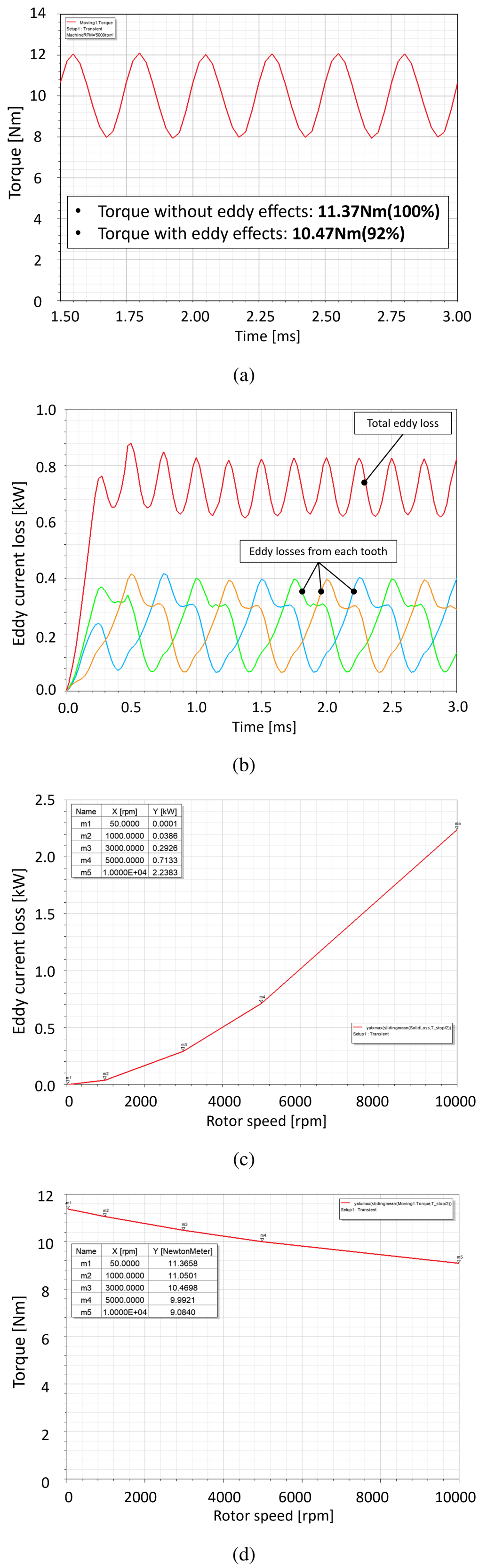


Fig. 8. Simulated performance of the additively manufactured AFPM machine with a detailed Hilbert pattern stator geometry. (a) Torque waveform, (b) Eddy current loss in the Hilbert pattern stator, (c) Stator eddy current losses at different rotor speeds, (d) Electromagnetic torque reduction due to eddy current effect at different rotor speeds.

VI. Conclusion

This paper studies the electromagnetic modeling of lattice structures in additively manufactured electric machines. It has been shown that 3D electromagnetic FE analysis with HPC exhibits the highest fidelity in predicting the electromagnetic performance of designs with lattice structures by preserving complex geometry details. The FE-based homogenization method for electromagnetic material properties has been explored to not only compare different lattice structures but also reduce the geometry complexity and computation time of whole electromagnetic device models, showing promising results. Future work will include the sensitivity of electromagnetic performance of additively manufactured electric machines on different design parameters, such as percentage of the volume filled by material, unit cell size, infill wall thickness, etc.

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