Interplay Between Acoustical and Mechanical Properties in Lattice Structures: A Geometrical Perspective

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The imperative for lattice structures to excel in both sound absorption and mechanical properties arises from the increasing demand for materials and structures that offer multifunctional solutions. However, the relationship between these two properties, and on how to design structures that excel in both, remains uncertain. Here, a perspective is presented on the interplay between sound absorption and mechanical properties in lattice structures, focusing on their mechanisms, limitations, and recommendations. First, a new term acoustical geometry is introduced to describe the features influencing sound absorption in lattice structures. Identified from the absorption resonance's structural requirements, acoustical geometries are derived from the actual lattices' structural features. Using this, links between sound absorption and mechanical properties are drawn. It is found that truss and triply periodic minimal surface lattices lack the design freedom needed to simultaneously customize sound absorption and mechanical properties, as both are inherently tied to the same structure. For the inherent capability of introducing pores strategically, this relationship is less intertwined for plate lattices. Therefore, it is advocated for the development of hybrid lattices with features that decouple sound absorption from mechanical properties, paving the way for new meta materials that enable customizable multifunctionality.

1. Introduction

The trajectory of lattice structures is steering toward multifunctionality, marking a paradigm shift in lattice structure design.[1] The ability to concurrently optimize various engineering properties within a single lattice structure heralds a new era of efficiency and adaptability. This advancement enables the design of highly integrated structures that do not compromise individual property while achieving synergistic functionality. For instance, this includes combinations of two or more of the following properties, such as mechanical, vibration, thermal, electromagnetic, and acoustic properties.[2–7] Among the myriad of functions that lattice structures can perform, the simultaneous enhancement of sound absorption and mechanical properties emerges as a frontier with far-reaching implications. The imperative for lattice structures to excel in both sound absorption and mechanical properties arises from the increasing demand for materials and structures that offer multifunctional solutions. Industries grappling with challenges such as noise pollution, structural integrity, and lightweight design seek innovations that can seamlessly integrate diverse functionalities. The ability of lattice structures to meet these requirements positions them as key players in the evolving landscape of advanced materials and engineering solutions.

For both mechanical and acoustical applications, there is no straightforward way to define the best properties universally. Instead, engineers seek customizable properties that are best fit for specific applications. For instance, in aerospace, the focus is on achieving a high strength-to-weight ratio to create lighter and more fuel-efficient aircraft. This often involves designs with anisotropic and directional features,[8,9] shell designs that reduce stress concentrations,[10] plate lattices,[11,12] etc. In the automobile industry, the emphasis is on high toughness and crash energy absorption to enhance vehicle safety. This usually includes structures with a more complex network of struts, functionally graded structures,[13] that are ideal for gradual bending deformation under compression. As a result, high-rigidity lattices may be better suited for structural purposes, while bending-dominated lattices, characterized by a long stress plateau, are more appropriate for

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energy absorption. In terms of acoustics, noise frequencies vary depending on the setting. For instance, vehicular cabin noises range from 100 to 300 Hz. In turn, perceived cabin noises in an aircraft usually range up to 1000 Hz.[14] The sound absorption properties, including intensity and working frequency, are closely related to the structure of the lattice. Therefore, for different applications where lattices are implemented, fit-for-purpose designs are highly sought after. This also implies that lattice structures should allow for design flexibility to simultaneously achieve different properties.

Thus far, a considerable number of studies have focused on lattice structures that exhibit both unique mechanical performance and sound-absorbing properties. Various types of unit cells have been explored, including those with features such as trusses,[15–18] plates,[17,19–22] tubes,[23,24] triply periodic minimal surface (TPMS),[25–29] anisotropic directional features,[30,31] and smooth skeletal structures.[32–35] These articles primarily report the individual sound absorption and mechanical properties of lattice structures. However, they often do not address the interplay between these properties or how they might be interrelated. Understanding this relationship is crucial because optimizing one property could potentially compromise the other. For instance, enhancing the mechanical strength of a lattice might require increasing the relative density, which could negatively impact its sound absorption capabilities by altering the resonant frequencies or reducing the porosity needed for effective acoustic damping.[23] This is evident in strut and TPMS structures, where increased strut or wall thickness reduces pore sizes, thereby limiting air movement and viscous dissipation resulting in reduced absorption resonance.[23,29] This means with increased mechanical properties, sound absorption in turn decreases in these structures. These observations highlight the need for a careful balance in designing multifunctional lattices, optimizing mechanical properties while preserving porosity and resonance for effective acoustic performance. Thus, this perspective aims to provide insights into the influence of lattice structure design on both mechanical and sound absorption properties. It will explore the fundamentals related to both properties, and introduce the concept of acoustical geometry, and how it is related to lattice geometry.

2. Brief Overview on Sound Absorption in Lattices

2.1. Sound Absorption Mechanisms

Numerous reviews have extensively analyzed the mechanical properties of lattice structures,[36,37] however, less on the sound absorption properties. To facilitate discussion, in this overview, we provide a concise introduction to sound absorption in lattice structures. Sound absorption, as the term implies, is the process by which a material takes in sound energy as sound waves travel through it. Sound waves move as longitudinal waves owing to the alternating pressure changes of the air molecules. This motion is detected by the cochlea in our ears or sensors in microphones, converting it into signals that are further processed and perceived as “sound”. Therefore, when the motion of these molecules is reduced, it leads to a perceived decrease in sound levels. Physically, sound absorption entails converting the kinetic energy of moving molecules into thermal energy.

In lattice structures, the main mechanisms of sound absorption are viscous flow and thermal dissipation.[38] The primary mechanism, however, is viscous flow dissipation at the viscous boundary layer. When air flows over a material, a viscous boundary layer forms as a transitional zone between the zero-velocity surface of the material and the bulk of the flowing air at its defined velocity. Air molecules in close proximity to the material experience significant frictional forces, which reduce their motion. As a result, the most substantial contribution to sound absorption comes from frictional dissipation at the viscous boundary layer. Thermal dissipation, caused by the thermal flux across the thermal boundary layer,[38] plays a minimal role compared to viscous losses.[39]

From the aforementioned mechanisms, it is apparent that absorption takes place via the interaction and dissipation of sound wave energy as the waves pass into the lattice structure. The stronger the interaction, the better the absorption. Thus, if there are resonance mechanisms in which the air molecules can vibrate the most intensively, this dissipation is enhanced. Due to their intricate structure, most lattice structures absorb sound through resonance. Consequently, different structures result in different dominant absorption mechanisms and different acoustical geometries.

2.2. Resonance Mechanisms

In lattice structures, two main mechanisms contribute to acoustic resonance: multi-layer Helmholtz resonance and cavity resonance. Most lattice structures absorb sound via Helmholtz resonance. This term is derived from the Helmholtz resonator, a bottle-like enclosure capable of trapping and amplifying specific frequencies of sound by utilizing the cavity and neck geometries. The greatest sound energy loss occurs at the neck during this amplification. The cross-section of a single Helmholtz resonator unit is shown in **Figure 1A**. The main geometries of concern include the pore diameter (d), pore thickness (t), and the depth of the air-backed cavity (D). Under cellular periodic arrangements, another important parameter is the surface porosity (σ), which refers to the ratio of the surface area of the pore, calculated with $\pi(d/2)^2$, to a unit area of the whole resonator, e.g., W^2. Then, for repeating resonators consisting of several layers, this mechanism is commonly referred to as multi-layer Helmholtz resonance (MLHR). An additional metric of concern is then N, the number of layers along sound incidence. Cavity resonators are then structures designed to trap and amplify sound vibration at specific frequencies through resonance. Commonly found cavity resonators include windpipe instruments. Again, this amplification results in the loss of sound wave energy. Herein, geometrical parameters of interest include the cavity diameter, or width, depending on the shape, w, and the total length of the cavity, L (Figure 1B). For cavities of a more torturous path, another derived parameter known as the tortuosity, χ, also needs to be considered. χ refers to the ratio of the actual path the sound wave travels through the structure (L_e), to the overall structure thickness (L). It accounts for the complexity of the path the sound wave travels.[40] Detailed mathematical descriptions of these parameters, the acoustic impedance calculations, can be found in a review by Li et al.[5] Herein, our main focus is on introducing

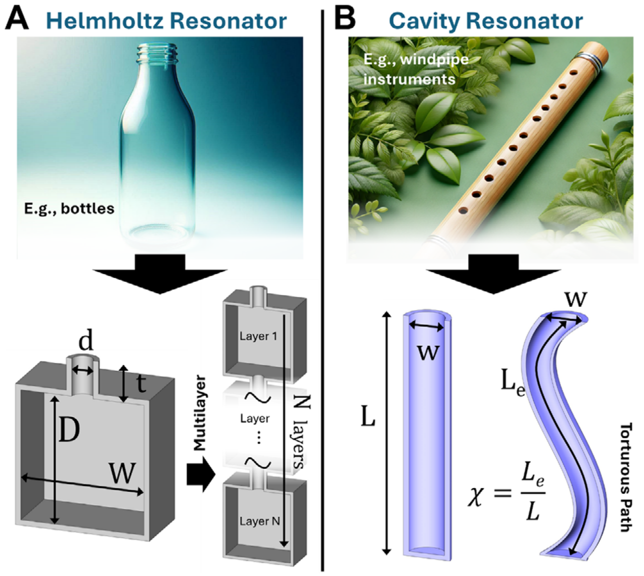

Figure 1. Schematic of resonance mechanisms in features found in lattice structures. A) Illustration of Helmholtz resonators and B) cavity resonators, including their geometries enabling the mechanism, and references to commonly found objects.

the main resonance mechanisms and the important acoustical geometries influencing sound absorption.

2.3. New Concept: Acoustical Geometries

Following the discussion on mechanisms, herein, we introduce a new term–acoustical geometry–to characterize lattice structures in terms of acoustics. Specifically, this term refers to geometries that have direct influences on sound absorption. Differing from the actual lattice geometries that influence mechanical properties, like strut diameter, and shell or wall thicknesses, identification of the acoustical geometry is non-trivial. Two steps are required for this, first, to know the sound absorption mechanism, and second, to infer the required porous geometries from the structure. This thus means that acoustical geometries are also mechanism-specific. For instance, this includes the various MLHR parameters introduced in the previous section, such as pore diameter, pore thickness, cavity depth, and structural resonance parameters such as the effective dimension and total length. These parameters are then derived from the type of lattice structure, relative density, and unit cell size. At this point, to illustrate acoustical geometries, we can refer to **Figure** 2A,B, which demonstrates the distinction between acoustical geometry and lattice geometry in truss lattices. This distinction is crucial, as acoustical geometries pertain to the sound resonance mechanisms, whereas lattice geometry pertains to the inherent structural design of the lattice. As can be seen from Figure 2B, acoustical geometries, namely d, t, D, are thus structure dependent, variant with respect to lattice relative density, cell size, and repetitions through thickness. While the unit cell size and the number of repetitions through the thickness play a critical role in determining sound absorption properties, their influence is predictable and consistent across all sound-absorbing structures. For example, larger cell sizes shift resonance peaks to lower frequencies, and increased cells along sound incidence generally result in a stronger average absorption coefficient.[5] Thus, our focus here is on the critical acoustical geometries unique to each type of lattice herein. This contrasts with mechanical properties, which remain unaffected by cell size and repetitions. At this moment, the link between acoustical geometries and lattice geometries is uncertain. The following sections attempt to draw links between the interplays of mechanical and sound absorption properties for the various types of lattices.

2.4. Lattice Geometry

While acoustical geometries represent the manifestations of sound resonance mechanisms, lattice geometry describes the inherent structure of the lattice itself. Despite the virtually limitless design possibilities for lattices, two intrinsic factors are sufficient to define a lattice structure: lattice morphology and relative density. Lattice morphology refers to the specific arrangement of features such as struts, shells, plates, tubes, or combinations thereof.[36,37] Herein, relative density, ρ^*, refers to $\rho^* = \rho_c/\rho_s$, essentially the ratio of the density of the lattice (ρ_c), to the density of its bulk material (ρ_s). In other words, it quantifies the volume fraction of the lattice structure relative to a fully solid bounding box. For instance, lattices with a higher relative density have thicker struts, shells, or cell walls. Detailed information on the different types of lattice structures and their geometries can be found in numerous review articles.[36,37]

3. Interplay for Truss Lattices

Although there can be an unlimited number of different types of truss lattices, truss lattices are typically defined as an array of struts, typically joined at nodes. Mechanical properties are dependent on their deformability through the bending or stretching of struts. Notably, Ashby et al. summarized that the differentiation between bending or stretching can be attributed to Maxwell's stability criterion.[41] The Maxwell's stability criterion is given by $M = b - 3j + 6$, where b and j refers to the number of struts and nodes, in a unit cell, respectively. A smaller M value tends toward bending and a higher M tends toward stretching. A structure with a higher M thus has more struts and a smaller number of nodes, and this usually means that the structure is more "complex" looking. Indeed, this is true comparing structures classic bending-dominated structures like the body-centered cubic (BCC) and stretch-dominated structures like the face-centered cubic (FCC) and simple-cubic (SC). Generally, stretch-dominated structures are stronger than bending-dominated ones. The prominent Gibson–Ashby relationship, an empirical power law relating properties and relative density (ρ^*), indicates that properties such as stiffness (E), strength (σ), and specific energy absorption (SEA) increase with increasing relative density.[37] As previously mentioned, ρ^* represents the volume fraction of the lattice structure relative to a fully solid bounding box. Naturally, as the strut diameter (d_{strut}) increases, ρ^* also increases due to the higher material volume. This increase in material volume intuitively enhances the lattice's resistance to deformation, either by strengthening bending moments or improving

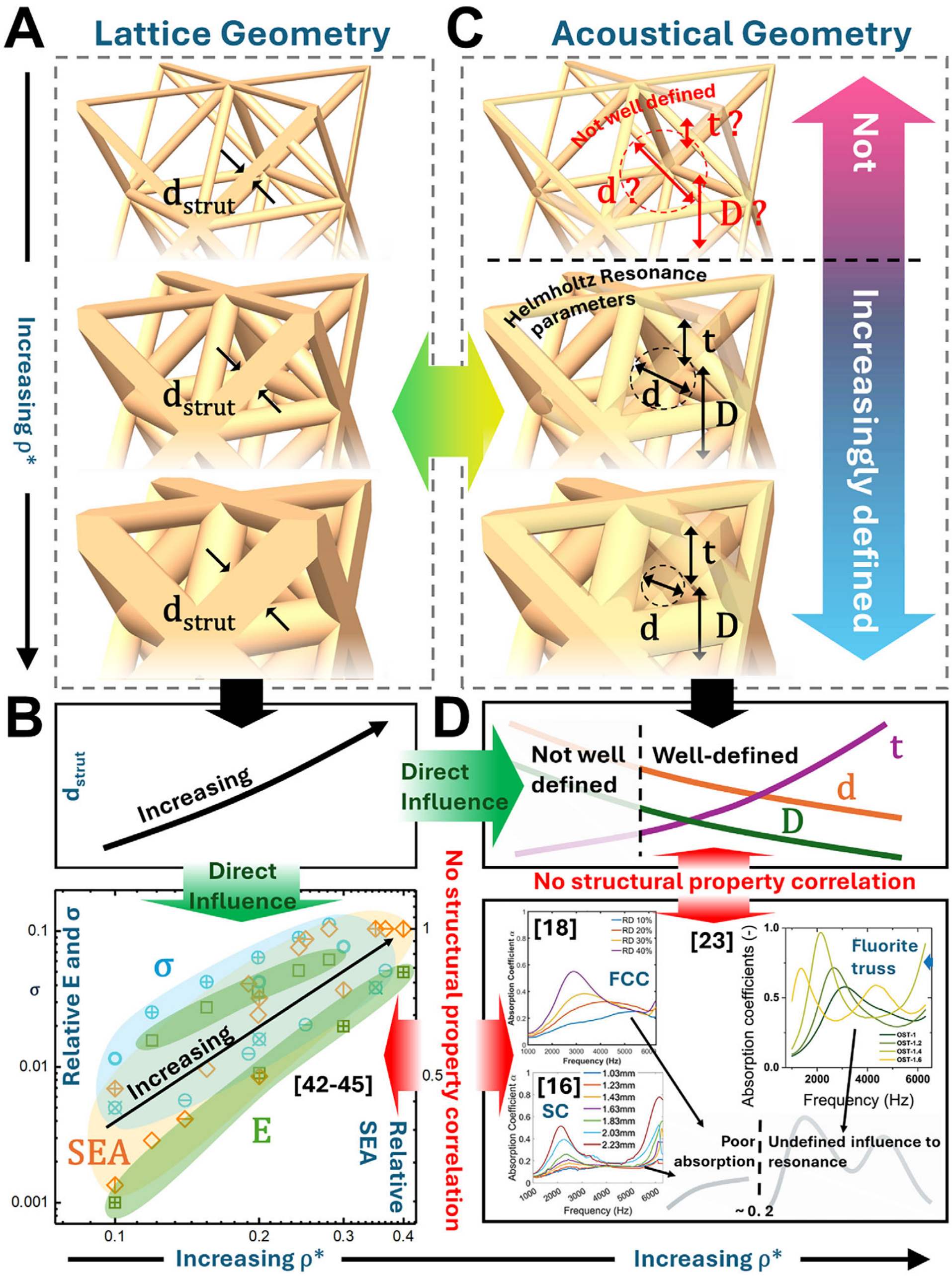

Figure 2. Overview of lattice geometry and acoustical geometry in truss lattice structures. A) Illustration of increasing strut diameters (d_{strut}), and its influence on B) relative density and mechanical properties, via data-driven plots.[42–45] C) Illustration of the influence of d_{strut} on the MLHR acoustical geometries, revealing that these geometries emerge only at sufficiently large d_{strut}, and that their dimensions vary with d_{strut}. D) The acoustical geometries lack a straightforward structural correlation with d_{strut}, thus leading to unpredictable resonance and sound absorption. Reproduced with permission.[18] Copyright 2024, Taylor & Francis. Reproduced with permission.[16] Copyright 2022, Acc Science Publishing. Reproduced with permission.[23] Copyright 2021, Wiley.

compression resistance through greater structural rigidity. This is affirmed in the data-driven trends, incorporating a wide range of truss lattices such as the SC+FCC,[42] BCC,[43] and einstein tiles,[44,45] plotted in Figure 2B. For E and σ, values are plotted relative to their bulk properties, while for SEA, the values are normalized to the SEA of the highest relative density studied. This approach eliminates material-specific influences, ensuring a clear illustration of the trends. Despite differences in deformation modes and property scaling, the plot affirms that mechanical properties increase with increasing relative density.

Similar to mechanical properties, the intricacies of sound absorption in truss lattices also hinges on the complexity of the arrangement of these structural elements and the relative density. However, there is no distinct relationship between absorption coefficients and these factors, unlike that for mechanical properties. Notably, the more complex the structure is (usually higher M), and the higher the relative density it is at, the better the sound absorption. This is attributed to the structure leaning more toward MLHR, characterized by alternating regions of small pores and large cavities within the lattice. This phenomenon can be explained by the following factors. First, the intricate arrangement of trusses in more complex structures tends to create heterogeneously architectured regions with both small and large pores. Second, the provision of necks, a prerequisite for MLHR, is achievable only with adequately thick struts. When the struts are thicker, immediate struts exhibit a lower inter-separation distance that results in smaller pores. In such a case, the strut diameter may constitute the pore thickness, t, while the closest region between two struts, constitutes the pore size, d.[23] This is exemplified in Figure 2C using a classic FCC unit cell, where the complex strut arrangements form the pore and cavity, and the d, t, and D parameters are well-defined only at moderately high relative densities. Indeed, as observed in the inset of Figure 2D, FCC lattices of only 30% or higher relative density display observable resonance.[18] Additionally, it can be observed that as the strut diameter increases, both d and D decrease while t increases. In turn, simpler structures like SC or BCC may develop the neck morphology required for MLHR only at very high relative densities, where the struts exhibit more pronounced curvatures (Figure 2D).[16,18] In these structures, thin struts lack the necessary thickness to form the required neck. Thus, values of the acoustical geometries (d, t, D), or even their existence, are determined by the lattice geometry d_{strut}. MLHR is more easily observed in complex trusses such as the fluorite truss (Figure 2D).[23] In this case, varying d_{strut} results in varying MLHR resonances with no distinct correlation.

Thus, for truss lattices, there is no direct mathematical or empirical relationship between the lattice geometry and acoustical geometries. While thicker struts (increasing relative density) generally promote increasingly defined MLHR parameters, with likely decreased d, D, and increased t, there is however no direct structural-property relationship determinable between these parameters. Due to the indeterminate acoustical parameters, there is also no systematic way of correlating them to the sound absorption properties. Thus, although mechanical properties and sound absorption properties are related to one another, there is however no direct structural-property relationship between the two in trusses (Figure 2D).

4. Interplay for TPMS Lattices

TPMS lattices are lattices with structures derived from the TPMS mathematical surfaces. There are two types of TPMS lattices, sheet TPMS–based on the thickened surface, and skeletal TPMS–based on the inverse of the thickened surface. As skeletal TPMS are truss-alike, more often, sheet-based TPMS is adopted for various applications. Examples of sheet TPMS are shown in **Figure 3A**. As can be seen, they often feature smooth surfaces with nearly uniform cavity cross-section sizes. For instance, owing to their zero mean curvature design, many TPMS structures display highly uniform separation distances.[25] In fact, for this property, TPMS lattices are often ideal candidates for flow applications,[10] such as heat exchangers,[46] and support structures to allow effective flow.[47] The key parameter describing the lattice geometry includes the wall thickness, t_{shell} (Figure 3A). Similar to truss lattices, through the data-driven plot on prominent TPMS lattices such as sheet Gyroid, Diamond, and Primitive,[48] we can see that increasing t_{shell} results in increased mechanical properties (Figure 3B). Owing to their smooth surface morphology, most do not display a distinct narrow neck and wide cavity morphology for the MLHR absorption mechanism. Sound absorption in these lattices is thus mainly based on dissipation through cavity resonance, with the exception of a high relative density Primitive TPMS that displays a narrow pore and wide cavity (Figure 3C).[49] Although there is only limited research being dedicated to the acoustical properties of TPMS lattices, research thus far nonetheless shows no distinct correlation between the type of TPMS architecture and sound absorption properties (Figure 3D).[25,29] Reports showed that generally, the higher the relative density, the stronger the resonance peaks.[25,28,29] However, no distinct correlation between the position of the peaks and relative density is revealed.[29] Also, an increase in the number of layers along the direction of sound incidence creates longer resonance cavities, leading to stronger resonance peaks that shift to lower frequencies.[28] Compared to truss and plate lattices, less is known for the sound absorption properties of TPMS lattices. Nonetheless, thus far, no structural-property correlation between sound absorption and mechanical properties has yet observed in TPMS lattices.

5. Interplay for Plate Lattices

Plate lattices consist of interconnected plates, typically fully joined at their edges. As a result, plate lattices exhibit a closed-cell structure, where the plates experience a membrane state of stress upon deformation. This closed-cell nature allows plate lattices to achieve superior stiffness and strength per unit weight compared to other lattice types.[12,50] However, closed-cell plate lattices are impractical to manufacture using vat-photopolymerization and powder-bed fusion 3D printing techniques, which are of significant engineering interest. These techniques lead to the entrapment of feedstock materials, rendering them unremovable. To overcome this limitation, researchers have introduced pores onto the plates to facilitate the removal of feedstock material.[11,12,51] These pores can be introduced at various locations, including nodes,[17] edges,[52] or on the plates.[19,22,53] For example, as illustrated in **Figure 4A**, in an FCC plate structure, Type I involves adding pores at the edges, while Type II involves adding pores at the faces. Therefore, in the context of plate lattices discussed here, we refer to those with pores introduced. Depending on the location and size of the pores, a proportional reduction in stiffness and strength may be observed in these lattice structures. Regardless, mechanical properties are determined by the plate thickness, t_{plate}. Also, like all lattice structures, relative density increases with increasing t_{plate}. Data-driven plot in Figure 4B encompasses popular plate lattice structures including Type I FCC,[54] Type II FCC,[53] SC,[53] and hybrid plate lattices,[55] and reveals how mechanical properties increase with increasing relative density.

In addition to 3D printability, the introduction of pores is crucial for allowing sound waves to pass through the lattices and achieve sound absorption. Thus far, plate lattices with

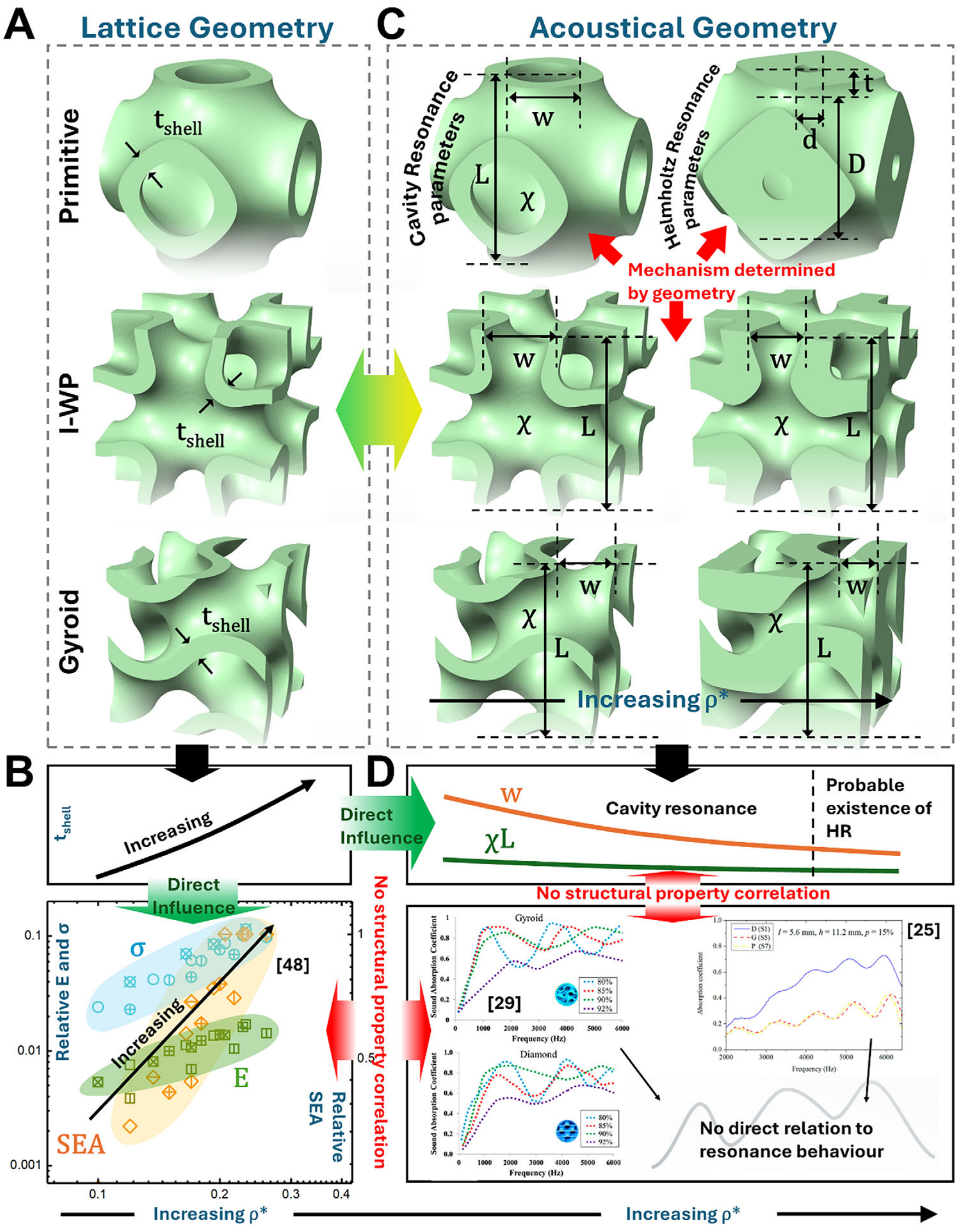

Figure 3. Overview of lattice geometry and acoustical geometry in TPMS lattice structures. A) Illustration of various types of TPMS structures and the concept of shell thickness (t_{shell}). B) Influence of t_{shell} on relative density and mechanical properties, via data-driven plots.[48] C) Illustration of the various possible resonance behaviors, and the influence of increasing t_{shell} on acoustical parameters in TPMS lattices. D) The acoustical geometries lack a straightforward structural correlation with t_{shell}, thus leading to unpredictable resonance and sound absorption. Reproduced with permission.[25] Copyright 2020, Taylor & Francis. Reproduced with permission.[29] Copyright 2024, Sage Publishing.

pores have been reported to exhibit sound absorption based on MLHR.[17,19,52] Specifically, the introduced pores constitute the pore (d), structural or plate thickness to the pore thickness (t), and immediate enclosed cell to the cavity depth (D), all of which are necessary for MLHR functionality (Figure 4C). The number of pores per unit cell then influences the surface porosity of MLHR. Pores in plate lattices have been introduced at various locations, such as nodes,[17] edges,[52] faces of plates,[19,22] resulting in MLHR behavior under different acoustical geometries. In MLHR-based lattices, a key distinction is that pores are inherently present in plate lattices, while in trusses or TPMS, their existence depends on structural complexity and relative density. Thus, it can be said that MLHR parameters exist in plate lattices regardless of structural complexity and relative density. This also implies that acoustical parameters are not as coupled with the lattice geometry as much as truss and TPMS lattices. The varying degrees of influence on acoustical geometries by the lattice structure are exemplified in Figure 4D. For instance, increasing t_{plate} results in decreased d since the pores are introduced at the edges in a Type I structure. Conversely, increasing t_{plate} has no

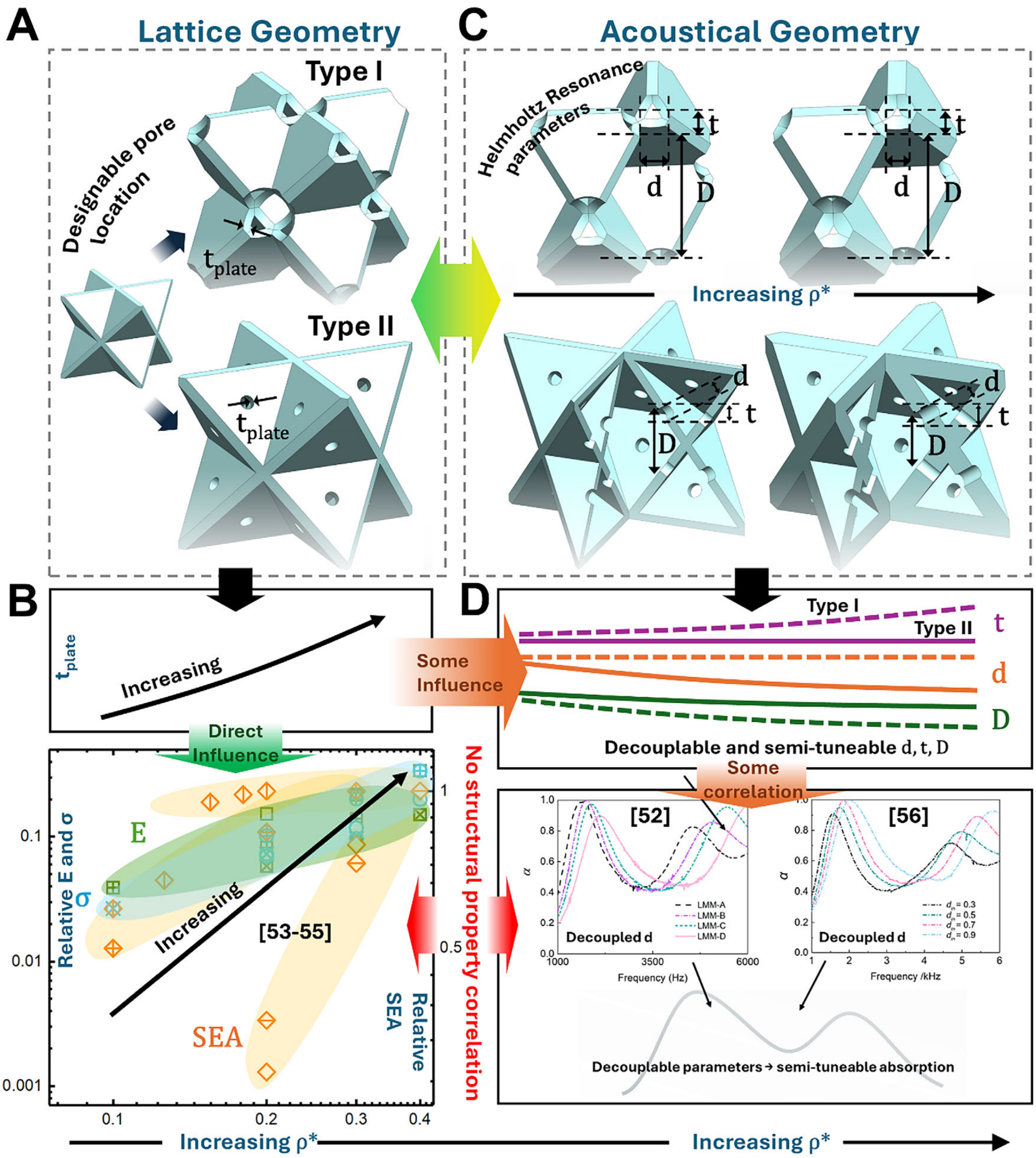

Figure 4. Overview of lattice geometry and acoustical geometry in plate lattice structures. A) Illustration of two types of FCC-based plate lattice structures and the concept of plate thickness (t_{plate}). B) Influence of t_{plate} on relative density and mechanical properties, via data-driven plots.[53–55] C) Illustration of the MLHR resonance behavior in plate lattices, and the influence of increasing t_{plate} on acoustical parameters. D) Plate lattices offer a greater degree of customizability, allowing the tuning of MLHR parameters for desired resonance and sound absorption. Reproduced with permission.[56] Copyright 2023, American Chemical Society. Reproduced with permission.[52] Copyright 2023, Taylor & Francis.

influence on d for the Type II structure since d is independent from t_{plate}. The same can be said for t and D, fully revealing the decreased degree of coupling. Additionally, the arbitrary introduction of pores provides an extra degree of design freedom. This allows for an increased degree of customization of target sound absorption properties through semi-tunable acoustical parameters. Insets in Figure 4D reveal the possibility of tuning d, keeping other factors constant, to achieve customizable sound absorption properties through this semi-decoupling.[52,56] Despite the increased acoustical design freedom, it is however still not possible to design resonance behavior based on the lattice design and thus acoustical geometry. Therefore, there is no direct structural-property correlation between sound absorption and mechanical properties in plate lattices.

6. Evaluation

For trusses and TPMS lattices, the structure dictates both properties simultaneously with no freedom for design (**Figure 5**). For instance, as mentioned in Section 3, in trusses, narrow pores and

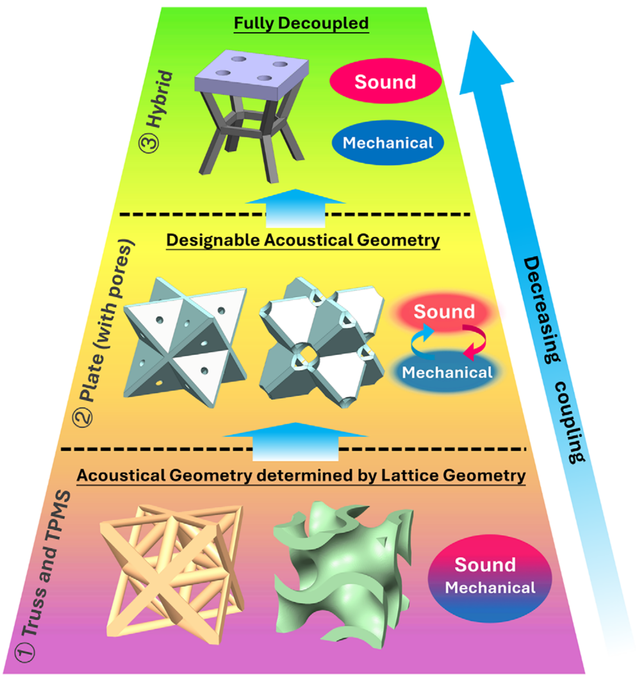

Figure 5. Schematic representation of the coupling between sound absorption and mechanical properties in different lattice structures. Truss and TPMS structures show a strong coupling where the acoustical geometry is directly determined by the lattice geometry, leading to intertwined mechanical and sound properties. Plate lattices with pores offer increased control over pore design, allowing for partial decoupling and tunable interactions between sound absorption and mechanical strength. Hybrid lattices achieve a complete decoupling of sound and mechanical properties, enabling independent optimization of resonance and structural performance.

wide cavities can only form if struts are sufficiently thick or the structure is sufficiently complex.[17,23] Thus, the existence of the MLHR mechanism depends entirely on the structure. Low relative density trusses, without the MLHR mechanism, display poor absorption.[16] This reveals the direct dependence of acoustical geometries on the lattice geometry, with no room for customization. Therefore, although we can change the truss morphology to achieve the desired mechanical properties, this may not align with the sound absorption requirements. The sound absorption properties of TPMS lattices are less studied; however, a similar trend is observed in these structures as well.

In contrast, plate lattices offer increased design freedom compared to truss and TPMS structures (Figure 5). Owing to the inherent capability of strategically introducing pores, the relationship between sound absorption and mechanical properties is less intertwined for plate lattices. For instance, as mentioned earlier, in trusses, pores exist only if struts are sufficiently thick, or the structure is sufficiently complex. However, in plates, pores are artificially introduced, and their existence is irrelevant with respect to the structure or the relative density. The closed-cell nature of plate lattices constitutes the wide cavities, fulfilling all requirements for MLHR. Indeed, for similar structures, pores can be introduced at different locations, such as nodes,[17] edges,[52] faces of plates,[19,21] resulting in drastically different acoustical geometries. This enhances customizability. In fact, for plate lattices, to a certain extent, we can strategically introduce pores to enable tailored sound absorption. In summary, for truss and TPMS lattices, both sound absorption and mechanical properties are entirely dependent on the same structure. It is not quite possible to change one property without influencing the other, thus leaving no room for property-specific customization. Plate lattices offer increased design freedom for customization, although both properties also depend on the same structure.

To achieve fully customizable properties, innovative designs and methodologies are essential. In this perspective, we advocate the development of hybrid lattice structures that allow the independent tuning of mechanical and acoustic properties. By decoupling these properties, hybrid lattices provide the flexibility to optimize sound absorption without compromising structural integrity, or vice versa.

7. The Way Forward: Hybrid Designs

Moving forward, we propose hybrid lattice structures as the benchmark structures for achieving customizable sound absorption and mechanical properties. Herein, hybrid lattice structures refer to those combining perforated plates, either flat or architectured, with support features below, where the support features can be in any form of lattice structures. In essence, this configuration embodies the required acoustical geometries required for the MLHR mechanism (**Figure 6**). The perforated plate acts as the pore, allowing sound waves to enter, while the immediate supporting structures beneath it serve to support the air cavity. The absorption performance, including resonance frequency and intensity, for MLHR absorbers depends primarily on the different combinations of pore diameter (d) and thickness (t), and the depth (D) of the cavity (Figure 6). With the geometry accommodating these features being inherently existing in a hybrid structure, full design freedoms are thus possible by changing their dimensions. According to various studies, as long as the cavity is not significantly occupied, features in the cavity do not influence sound absorption.[57] If the cavity volume is significantly reduced due to the presence of features, a slight correction factor can be applied to the cavity depth to account for this.[17,58] However, the influence of the cavity depth on sound absorption is minimal compared to that of the pore.[35] The cavity is thus adaptable to accommodate different structural components, as exemplified in Figure 6A. This way, full control over E, σ, and SEA, as per trends for truss, TPMS, and plate lattices, can be achieved in hybrid lattices by adopting these different mechanical elements (Figure 6B). Further, full control over large strain deformation can also be achieved, for instance, high strength,[57] high toughness,[57] or recoverability[31] using different structure designs and materials (Figure 6B). Similarly, there is complete design freedom with the pores, allowing variations in pore diameter (d), depth (t), height separation between pores (D), and even shape and surface porosity, just like how MLHR-based acoustic metamaterials can be designed (Figure 6C).[59] With these customizable pore geometries and adjustable cavity depth, full control over resonance behavior and sound absorption properties can be achieved. This is demonstrated in Figure 6D-i, where both hybrid lattices—one with SC struts and the other with BCC struts—exhibit nearly identical sound absorption behavior.[57] Meanwhile, Figure 6D-ii highlights the potential for achieving

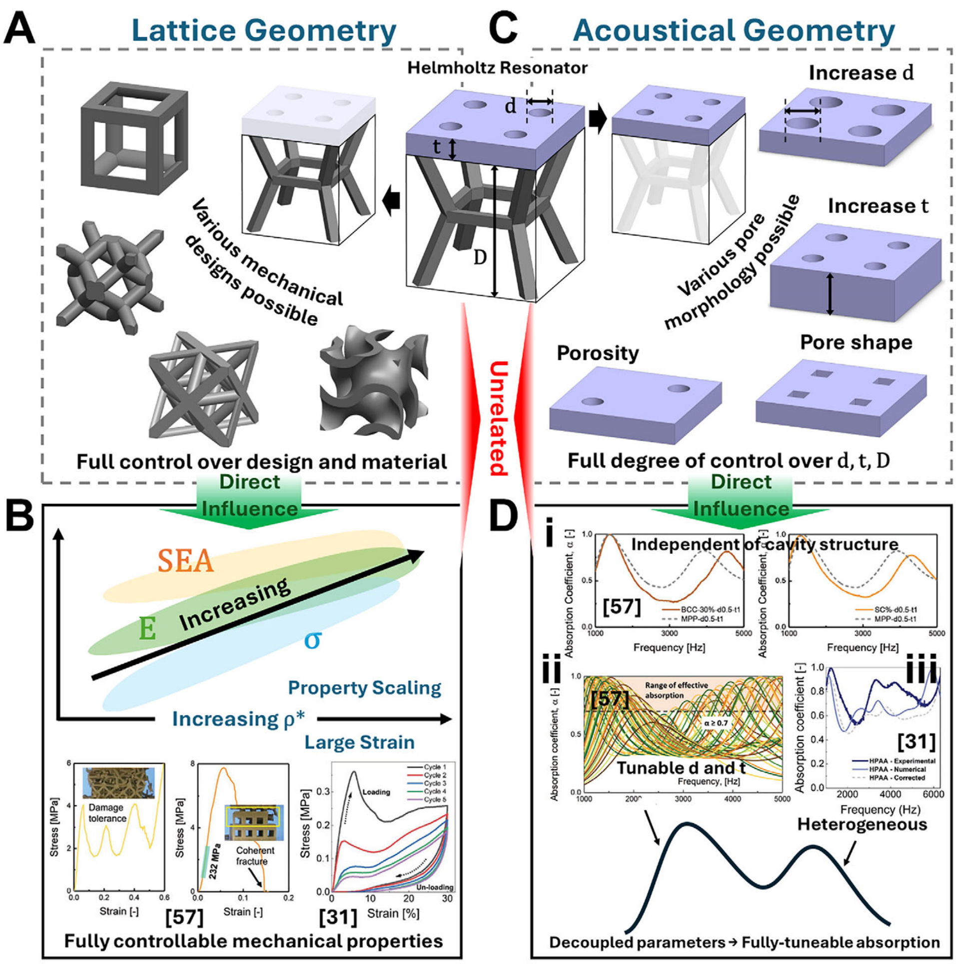

Figure 6. Overview of the hybrid lattice structure concept, based on Helmholtz resonator principles. A) Demonstration of the flexibility in selecting lattice geometry within the cavity, revealing the B) fully customizable mechanical properties via different lattice geometry and material selection. C) Demonstration of the flexibility in pore morphology design within the plate. D) Fully customizable acoustical geometries that are independent of mechanical elements can be achieved, allowing precise tuning of resonance and sound absorption. Reproduced with permission.[57] Copyright 2024, Wiley. Reproduced with permission.[31] Copyright 2021, Wiley.

strong resonance absorption across a wide frequency range simply by tuning the parameters d and t.[57] Additionally, by incorporating heterogeneous pore morphologies in the plate, broadband absorption can be realized through the synergy of multiple resonance modes (Figure 6D-iii).[31] By independently tuning the fully decoupled parameters d, t, and D, along with the option to introduce heterogeneity, fully customizable sound absorption can be achieved (Figure 6D).

Indeed, various studies have explored different combinations of plate-pore morphology and cavity features for different applications. A diverse range of acoustic and mechanical properties has been achieved by combining various cavity and plate designs with different materials. Thus far, cavity features investigated include trusses,[31,35,57] wavy walls,[30,60] regular cell walls,[61] and TPMS[62,63] beneath the perforated plates, all designed to achieve different mechanical properties. Beyond tuning the acoustical parameters, another common approach to enhancing sound absorption is incorporating heterogeneously sized pores (d and t) on the perforated plate. This enables broadband absorption by leveraging multiple resonant cells working in tandem.[30,31,35,61] Apart from d and t, D can also be varied.[30,31] Compared to traditional lattices, heterogeneous features can be seamlessly incorporated into hybrid designs due to their ability to introduce acoustic geometries in a fully decoupled manner. For structures based on trusses, deliberate partitions are introduced to create separate resonance chambers.[31,35] For structures based on plates or cell walls, these features inherently serve as partitions, allowing the formation of isolated resonance chambers.[30,61] In addition to broadband absorption, the cavity feature design enables additional mechanical functionalities. For example, a heterogeneously porous hybrid lattice with embedded polymeric auxetic struts achieves a high compressive strength of ≈360 kPa while maintaining strain recovery from compressive strains up to 30%.[31] This effectively forms a durable, deformation-recoverable sound absorber, making it ideal for applications requiring both impact protection and acoustic control. The enhancement of sound absorption and mechanical performance can also be synergic at times. For another lattice design, heterogeneously partitioned bioinspired wavy cell walls cells were introduced to both enhance sound absorption and mechanical damage tolerance. At a low thickness of 21 mm, a high average absorption coefficient of 0.735 across the frequency range of 1000 to 6300 Hz is displayed.[30] The heterogeneous architecture enabled a high strength of 6.54 MPa with high damage tolerance at a specific energy absorption of 5.1 J g^{-1} even when the lattice is fabricated using rigid polymers. Such lattices may then be useful as strong and tough materials with yet strong sound absorption. These properties are achieved under the assumption that the structures within the cavity do not influence the sound absorption properties. This is further exemplified in another study, where the authors demonstrated various mechanical properties using the same perforated plate, which provided consistent sound absorption properties.[35] In recent works, it has also found that strategic placement of features in close proximity to the pore can enhance sound dissipation to a notable extent.[30,61] Overall, for hybrid lattices, the factors affecting mechanical properties and sound absorption are completely independent and decoupled. This independence allows for full customizability without the constraints of having to consider one property at the expense of the other.

8. Conclusions and Outlook

In summary, the interplay between mechanical and acoustic properties in lattice structures presents both challenges and opportunities. In this study, we critically analyzed the factors influencing sound absorption and mechanical properties across the three main classes of lattice structures—truss, TPMS, and plate—and concluded that, despite varying correlations between acoustical and lattice geometries, there is no direct structural-property relationship between these properties. This is mainly due to the fact that sound absorption properties are not linearly predictable based on acoustical geometries. Truss and TPMS lattices exhibit a direct dependence between their structural design and the resulting properties, limiting the ability to independently optimize sound absorption and mechanical performance. The inherent coupling in these lattices means that modifications to enhance one property often adversely impact the other, thereby restricting design flexibility. For example, while feature (strut or shell) thicknesses may dictate mechanical properties, an increase in thickness can drastically alter MLHR acoustical parameters, such as pore dimensions and cavity depths, without a direct correlation. In turn, plate lattices, embedded with pores, offer more design freedom due to the ability to arbitrarily introduce pores. This allows increased tunability with the pore design, thereby providing better control over sound absorption. However, despite this increased freedom, a direct structural-property correlation between sound absorption and mechanical properties in plate lattices remains elusive.

The development of hybrid lattice structures, which combine various features such as horizontal perforated plates with supporting elements beneath, offers a promising pathway to achieve true multifunctionality. One of the key benefits of hybrid lattice structures lies in the deliberate separation of acoustical and mechanical geometries, which is crucial for achieving a decoupled design. In these structures, the perforated plate primarily governs the acoustical behavior, acting as the resonant element that can be fine-tuned for specific sound absorption characteristics. The supporting elements, which may include trusses, walls, or other features, provide the necessary mechanical strength and stability. Because these two functions—acoustical and mechanical—are handled by distinct parts of the structure, each can be optimized independently without negatively impacting the other. This decoupling is crucial for creating materials that can meet specific requirements across diverse applications. Ultimately, advancements in lattice structure design aim to meet the growing demand for materials that excel in multifunctional applications, balancing sound absorption and mechanical performance. Future research and innovation will focus on refining these designs, enhancing their applicability across industries such as aerospace and automotive, where customized properties are essential. By exploring the potential of hybrid lattice structures, the path forward will involve developing materials with unprecedented versatility and performance.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

3D printing, lattice structure, mechanical properties, multifunctional, sound absorption

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