

A Discussion on the Similarities Between Mechanical Metamaterials and Soft Matter and the Possibilities for Their Combined Development

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Abstract

Mechanical metamaterials and soft matter, as frontier branches of materials science, extend the performance boundaries of conventional materials through artificial structural design and intrinsic responsive behavior, respectively. This paper briefly introduces these two fields and examines their similarities. It further discusses the possibility of their innovative integrated development as an approach to addressing certain limitations in each field, such as employing the stimulus responsiveness of soft matter to overcome the functional static nature of mechanical metamaterials, and utilizing the structural design paradigm of mechanical metamaterials to enhance the response speed and fatigue resistance of soft matter.

Keywords

mechanical metamaterials, soft matter, similarity, integrated development

1. Introduction

Mechanical metamaterials and soft matter are both important branches of materials science, and each exhibits unique and superior properties that are not found in conventional materials. For this reason, research on mechanical metamaterials and soft matter is both necessary and highly promising. At present, studies on both fields have extended into a wide range of domains, with their application scenarios continuously expanding and showing a strong tendency toward interdisciplinary integration. Moreover, the research on mechanical metamaterials and soft matter overlaps substantially in terms of concepts and methodologies, and the two types of materials themselves share certain similarities. Combining the two, allowing them to inspire each other and develop in an integrated manner, may represent a highly promising direction capable of generating innovative outcomes.

2. Mechanical Metamaterials

Mechanical metamaterials, also referred to as mechanical meta-materials, are a class of artificially engineered materials that exhibit special and superior mechanical properties distinct from those of conventional materials [1]. Their mechanical properties are determined not only by their constituent

materials but also by their mesostructure. Owing to the unique mechanical characteristics enabled by artificial design, mechanical metamaterials have been widely applied in various fields.

Several common types of mechanical metamaterials have been developed, including ultra-light, ultra-stiff metamaterials, zero or negative Poisson's ratio metamaterials, negative compressibility metamaterials, negative thermal expansion metamaterials, and pentamode metamaterials.

Ultra-light, ultra-stiff metamaterials overcome the traditional trade-off between stiffness and toughness, as well as between high strength and low density. By designing and regulating the micro- and nanoscale structures within mechanical metamaterials and reducing the characteristic dimensions of the structural elements, these materials can achieve high stiffness, strength, toughness, and excellent energy absorption performance even at low density [1]. In other words, unlike conventional materials that tend to be "heavy" when they are "strong," such materials are not only lightweight but also mechanically robust. This combination of high strength and low density has significant application value, for example in aerospace structures and military equipment.

Poisson's ratio is defined as the negative ratio of the transverse strain to the axial strain when a material is subjected to tensile or compressive loading. For the vast majority of conventional materials, Poisson's ratio is positive. This means that when a material is compressed in the vertical direction, it expands in the horizontal direction, appearing visually "flattened," which conforms to common intuition. Negative Poisson's ratio materials exhibit the opposite behavior: when compressed in the vertical direction, they also contract in the horizontal direction; when stretched horizontally, they expand in the vertical direction. This phenomenon is referred to as auxetic behavior. Certain structural configurations, such as re-entrant structures, chiral structures, rotating polygons, corrugated plates, and origami-inspired architectures, can endow materials with a negative Poisson's ratio. In kirigami mechanical metamaterials, for example, by designing and modifying the geometric patterns of the cuts, it is even possible to achieve a transition between positive and negative in-plane Poisson's ratios [1].

Compressibility refers to the relative change in volume of a fluid or solid in response to pressure variation and is the reciprocal of the bulk modulus K . Negative compressibility mechanical metamaterials exhibit a volumetric expansion response under hydrostatic pressure [1]. In simple terms, unlike conventional materials whose volume decreases under pressure, negative compressibility metamaterials expand as pressure increases. Negative thermal expansion is somewhat analogous to negative compressibility. In contrast to conventional materials that expand when heated, materials with negative thermal expansion undergo linear contraction or volumetric shrinkage upon heating, meaning that they become smaller as temperature increases.

Pentamode metamaterials, also referred to as metafluids, are artificially engineered three-dimensional solid structures that behave similarly to fluids and possess an extremely large ratio of bulk modulus to shear modulus (B/G). The shear modulus (G) generally describes shape change under constant volume, and in ideal gases or liquids this value is zero. The bulk modulus (K), by contrast, describes volume change under constant shape. In pentamode metamaterials, the shear modulus is close to zero relative to the bulk modulus, allowing them to be approximated as ideal fluids. In theory, they can serve as building blocks for materials with arbitrarily designed elastic properties and exhibit significant advantages in vibration and shock isolation.

Overall, mechanical metamaterials not only possess a wide range of significantly enhanced mechanical properties but also offer the possibility of creating unprecedented "super materials" through artificial design and fabrication, indicating enormous development potential. Nevertheless, mechanical metamaterials also face several challenges. For example, functional staticity, meaning that their ability to adapt to dynamic environments or changing tasks remains limited; discrepancies between theoretical models and fabricated structures caused by insufficient manufacturing precision, which may lead to deviations between actual performance and theoretical design or even unexpected failure; and the fact that most metamaterial designs are based on small-deformation linear theories. When subjected to large deformations, structures may lose their designed functionality due to buckling, plastic hinge formation, or fracture, and conventional small-deformation linear theories become inadequate for describing such nonlinear behavior.

3. Soft Matter

Soft matter, also referred to as complex fluids [2], is an important branch of condensed matter physics and materials science. It refers to materials that lie between ideal solids and ideal fluids and exhibit significant responses to weak external stimuli, such as temperature, pH value, electric fields, chemical signals, and mechanical forces. In other words, soft matter is characterized by a weak-input–strong-response behavior. It is generally composed of macromolecules or molecular aggregates and typically exhibits large deformation, high dissipation, and nonlinear behavior. Soft matter is termed “soft” because, compared with hard materials such as metals, semiconductors, and ceramics, it lacks the rigid structural framework characteristic of solids [3]. However, this “softness” is not its most essential feature; rather, the remarkable property of soft matter lies in the strong response induced by weak perturbations.

The core physical characteristics of soft matter are entropy dominance and self-organization. Unlike conventional hard materials, whose macroscopic properties are dominated by strong intermolecular interactions and internal energy, the macroscopic behavior of soft matter is often governed by entropy. Taking rubber as an example, when polymer chains are in a randomly coiled configuration, their conformational entropy is maximized. When rubber is stretched, the molecular chains are straightened, resulting in a decrease in entropy. After the external force is removed, the system tends to return to a high-entropy state, generating an entropic restoring force. This mechanism is fundamentally different from the internal-energy elasticity arising from bond length and bond angle variations, as in the case of a spring. Self-assembly in soft matter refers to the spontaneous organization of components into long-range ordered structures through noncovalent interactions, such as van der Waals forces and hydrogen bonding. For example, liquid crystal molecules can spontaneously arrange within a certain temperature range to form a mesoscopically ordered phase that lies between a liquid state and an isotropic solid state. This ability for self-organization forms the basis for the functionalization of soft matter systems.

The functional core of soft matter lies in its intelligent responsiveness. This responsiveness arises from the presence of multiple metastable states with comparable energy levels within the system. Weak external perturbations are sufficient to drive transitions between these states. External fields modify the interaction energies among components or directly affect molecular conformations, thereby disrupting the original entropy or internal-energy balance and driving the system toward a new equilibrium state. At the macroscopic level, this process manifests as phase transitions, volume changes, abrupt variations in rheological properties, or shape transformations.

Soft matter exhibits the characteristic of strong responses to weak stimuli, enabling it to sense changes in the surrounding environment. As a result, it possesses a wide range of potential applications and considerable prospects for future development. Nevertheless, soft matter also faces several challenges, such as difficulties in performance prediction and control. The mechanical behavior of soft matter is highly nonlinear and strongly dependent on loading history, environmental conditions, and the dynamic evolution of microstructures, making it difficult to achieve precise and deterministic design and prediction as in classical solid mechanics. In addition, soft matter systems often suffer from slow response speeds—since their responses typically depend on diffusion processes or phase transitions—as well as fatigue susceptibility and rapid degradation of mechanical performance, indicating substantial room for further development.

4. Similarities Between Mechanical Metamaterials and Soft Matter and Possible Pathways for Their Integrated Development

At first glance, the fields of mechanical metamaterials and soft matter appear to emphasize different aspects: the former focuses on rigid structural design, whereas the latter emphasizes flexible responsive behavior. However, at a fundamental level, the two share strong conceptual resonance.

First, both fields highlight the relationship between structure and properties. For metamaterials, macroscopic or mesoscopic structures determine mechanical properties. For example, the elastic tensor of a material can be “programmed” by modifying parameters such as lattice constants or the angles of structural members. Similarly, in soft matter, micro- or mesoscopic structures—such as the network topology of polymer chains or the arrangement of colloidal particles—govern their rheological and mechanical behavior. Many such systems exhibit characteristics of **isostatic systems**, allowing them to maintain structural integrity and stability even under internal bending or global deformation [4].

Second, both systems make use of instability and nonlinearity. In mechanical metamaterials, structural buckling and instability can be deliberately exploited to achieve abrupt functional transitions, such as buckling-induced negative stiffness, multistable structures, and shape reconfiguration. In soft matter, instability often plays a key role in its responsive behavior, for example in gel phase-transition instabilities, wrinkle formation, and shear banding.

Another notable similarity lies in multistability. In mechanical metamaterials, structures can be designed with multiple stable equilibrium states, enabling switching between different configurations under external stimuli. In soft matter systems, many materials—such as liquid crystal elastomers [5] and certain biopolymers—naturally possess bistable or multistable conformations.

The integration of mechanical metamaterials and soft matter may provide potential solutions to several challenges encountered in both fields.

As mentioned above, mechanical metamaterials often face the issue of functional staticity. Soft matter exhibits excellent stimulus responsiveness; therefore, stimulus-responsive materials—such as liquid crystal elastomers or hydrogels—could be incorporated as structural units or connectors within metamaterials. In this way, external fields (e.g., light, heat, magnetic fields, or pH changes) could dynamically and reversibly tune the geometric parameters of the metamaterial, thereby altering its macroscopic properties in real time, such as switching between positive and negative Poisson's ratios or turning band gaps on and off. This approach would enhance the ability of metamaterials to adapt to changing environments. In simple terms, soft matter could function as a “switch” that senses environmental changes and modulates metamaterial structures through its own deformation. For instance, the Bertoldi group at Harvard University embedded magnetically responsive soft particles into a flexible polymer matrix to form a periodic lattice, enabling real-time and reversible tuning of lattice stiffness and band gaps through an external magnetic field, thereby achieving switchable vibration control. This approach closely resembles the concept described above [6].

The challenge of failure under large deformation in mechanical metamaterials may also be addressed through integration with soft matter. Soft materials possess intrinsic flexibility and excellent large-deformation capability. If metamaterial structures are constructed from soft polymers or elastomers, such metamaterials could theoretically maintain structural integrity and designed functionality even under large deformations. At the same time, they would naturally exhibit compliance, biocompatibility, and energy dissipation capability, potentially expanding the applications of mechanical metamaterials in areas such as tissue engineering and wearable devices.

For the difficulty of predicting the performance of soft matter systems, the deterministic design principles of mechanical metamaterials may provide a useful approach. Soft materials could be architected into precisely designed periodic topological structures—such as hexagonal, chiral, or rotating-square geometries. In this case, the macroscopic mechanical behavior would be dominated primarily by geometrically predictable structural deformation rather than the complex statistical behavior of molecular chains. This would facilitate the prediction and even the “programming” of the large-deformation behavior of soft matter.

Regarding the issues of slow response and fatigue in soft matter systems, integration with mechanical metamaterials may also offer solutions. Soft matter responsive units could be miniaturized and arranged in arrays, for example by integrating multiple microscale hydrogel elements into a single metamaterial unit. This strategy would shorten diffusion pathways and thereby accelerate the overall response speed. In conventional homogeneous soft materials, such as bulk hydrogels, stress is often distributed unevenly under compression or tension, leading to stress concentration at defects, crack tips, or clamped boundaries, which may cause premature fracture. Inspired by mechanical metamaterials, carefully designed periodic structures with specific mechanical characteristics—such as auxetic or bending-dominated architectures—can actively manage and redistribute internal stress fields, thereby preventing excessive stress concentration at weak points (e.g., defects or boundaries) in soft matter systems and improving their reliability and practicality. For example, the research group of Xuanhe Zhao at MIT developed “hydrogel metamaterials,” in which hydrogels were designed as high-aspect-ratio fibrous network structures (similar to ligaments). This design increased toughness by tens of times while maintaining high water content and significantly accelerated swelling and deswelling rates [7].

Overall, the integration of mechanical metamaterials and soft matter is expected to provide new strategies for addressing key challenges in both fields. The stimulus responsiveness of soft matter introduces dynamic adaptability into mechanical metamaterials, enabling them to evolve from static structures into programmable and reconfigurable intelligent systems. Conversely, the deterministic structural design paradigm of mechanical metamaterials offers a powerful framework for predicting and controlling the complex nonlinear behavior of soft matter, while strategies such as stress guidance and miniaturized arrays can enhance the response speed and durability of soft matter systems.

5. Conclusion

Mechanical metamaterials and soft matter represent two distinct yet complementary paradigms in materials science. The former takes “structure determines properties” as its core principle, endowing materials with extraordinary mechanical properties through carefully designed topologies. The latter is characterized by “function realized through responsiveness,” relying on entropy-dominated behavior and weak intermolecular interactions to exhibit sensitive responses to external stimuli. The integration of these two systems is not merely a simple superposition but rather a synergistic paradigm in which structural design empowers responsive intelligence, while responsive behavior endows structures with dynamic adaptability. With the continuous advancement of research, the convergence of mechanical metamaterials and soft matter will undoubtedly open new avenues for the development of engineering materials and structures capable of environmental sensing, autonomous adaptation, and functional self-repair.

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Conflicts of Interest

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