MECHANICAL METAMATERIALS

Materials that push back

Proposed mechanical metamaterials that contract under tension and expand on compression represent a new approach to realize mechanical properties yet unknown in nature that could lead to applications in microelectromechanical systems.

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When a system is compressed from all sides by a hydrostatic pressure, it typically contracts in all directions. A few systems, however, have been reported that show negative compressibility — they expand in at least one direction when hydrostatically compressed[1–8]. Indeed, for constrained systems, negative compressibility does not violate the laws of thermodynamics[4]. Various mechanisms have been proposed to explain the occurrence of this phenomenon, ranging from the use of bi-material strips, whose components have different properties[5], to systems that exhibit this property due to their particular geometry[6,7] or due to constraints[4,8]. Writing in *Nature Materials*, Zachary Nicolaou and Adilson Motter now propose a metamaterial that exhibits a negative-compressibility transition by a mechanism based on force potentials[1] that represents a new way of achieving negative compressibility.

Metamaterials are usually associated with artificial materials that have anomalous optical or acoustic properties. Owing to their unusual behaviour, metamaterials can be used in a variety of applications such as acoustic shielding, electromagnetic cloaks or subwavelength lenses. Nevertheless, as the study by Nicolaou and Motter shows, metamaterials need not be of the electromagnetic or acoustic type but can also be mechanical. Metamaterials are engineered systems that exhibit macroscopic properties that emerge due to the structure of their subunits rather than their materials composition. Typically, these systems are designed to exhibit anomalous macroscopic properties such as zero or negative ratios, moduli and/or indices, which are not normally exhibited by naturally occurring materials.

The theoretical metamaterial suggested by Nicolaou and Motter also has new properties — it consists of a system that should suddenly increase in volume at an increasing applied pressure (Fig. 1). This behaviour is very different from normal materials that shrink in the direction of an applied pressure, and it is not observed in auxetic metamaterials either, which expand in the lateral direction as a consequence of being uniaxially stretched. In the metamaterial proposed by Nicolaou and Motter the expansion occurs in the direction of the applied pressure.

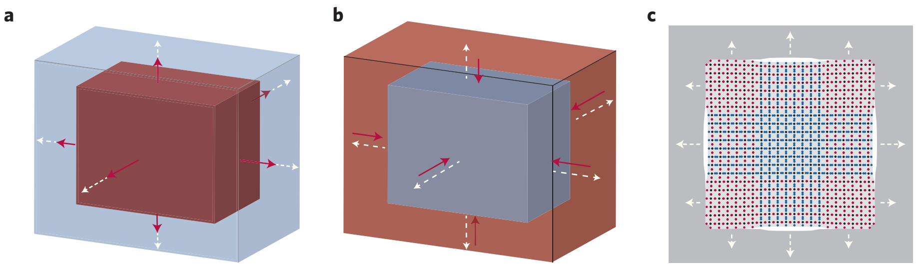

Figure 1 | Negative compressibility. **a**, A normal material under tension expands. The white arrows show the direction of the force, the red arrows the reaction of the material. **b**, The mechanical metamaterial showing the contraction of the proposed negative-compressibility transition under tension. **c**, The negative-compressibility transition is based on nonlinear interaction potentials between the materials' constituents. The red and blue denote the constituents two equilibrium states, with blue representing the compressed state[1].

This atypical property arises from the metamaterial's unusual negative response along the direction of an applied external force. This scheme is based on an unusual manner in which the metamaterial's subunits, its 'atoms', are bonded together through forces having atypical potentials. The potentials are designed such that these atoms have two stable geometric configurations of different size. The application of an external force can then lead to a sudden transition from one state of equilibrium to another, which expands the material in the direction of the applied pressure. The researchers term this behaviour a negative-compressibility transition.

The basic reasoning behind the proposed mechanism is the idea that if a large enough force is applied on the system, then its equilibrium can become disturbed, forcing it to move to a new state, possibly one that corresponds to a dilation when the system is hydrostatically compressed, if the interatomic potentials so dictate. In other words, a negative-compressibility transition is achieved. What distinguishes Nicolaou and Motter's way of thinking from the conventional ideas presented in textbooks is that here a non-infinitesimal small force is being applied, as what happens in real-life situations, together with the fact that the interatomic potentials must be chosen carefully so as to sanction the anomalous behaviour. In classical textbooks it is always assumed that infinitesimally small forces are applied, that is, ones that do not disturb equilibria. This mechanism differs from those that are typically used to achieve negative compressibility as it does not consist of a stretch densification mechanism, but rather a mechanism that is based on abnormal properties of the bulk. In itself, this may be a limitation for the proposed mechanism as negative-compressibility materials cited in the literature and even naturally occurring ones tend to display typical bulk behaviour unlike what is reported here. This might make the identification of suitable constituents for such metamaterials difficult. Also it is unlikely that the proposed model will be able to offer an easy way forward for identifying naturally occurring materials that exhibit these anomalous properties. Nevertheless, this doesn't hinder the validity of the model because it should remain applicable for metamaterials having the properties as specified by Nicolaou and Motter.

Applications for materials exhibiting negative compressibility are typically associated with structures where it is desirable that compression is to be avoided, such as telecommunication lines or sensors present in high-pressure environments such as those found in deep oceans[2]. Owing to its different underlying mechanism, the metamaterial proposed by Nicolaou and Motter should also exhibit force-amplification transitions, which means that it could be used in microelectromechanical systems or actuators — if this hypothetical structure can be implemented in practice. Nevertheless, as the occurrence of negative compressibility is quite rare, the work of Nicolaou and Motter may further stimulate studies in a field that is still far from being exhausted. More mechanisms that give rise to negative compressibility may be suggested based on the approach taken by the researchers. Such advanced studies could deepen the knowledge of negative-compressibility systems and explore new means of exploiting such materials for hitherto unimagined applications. ❐

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