How to make a material that shrinks when stretched

May 24, 2012 5 comments

Bizarre bulge on a metamaterial bowling alley

New metamaterials that shrink under tension and expand under compression might soon become a reality thanks to theoretical work done by scientists in the US. The researchers say the materials – which at first glance appear to violate the laws of physics – could be manufactured using currently available technology.

Metamaterials are synthetic materials that are often engineered to have properties not found in nature. Some of the most familiar have bizarre optical properties such as negative indices of refraction and have been used to create invisibility cloaks. More recently, research has also focused on metamaterials engineered to have exotic mechanical properties. These respond in unexpected ways to applied forces. For example, foams have been produced that get fatter rather than thinner when stretched.

Unstable equilibrium

Of particular interest is the possibility of manufacturing metamaterials that have a negative compressibility. That is they shrink under tension and expand under compression. Some materials already do this in response to a rapidly varying sinusoidal force – a result of time lag between the applied force and the resulting deformation. However, it had been assumed to be impossible to make a material that responded in this way to a constant force because such a material would have to exist in an unstable equilibrium.

If you take a rod of any normal material and apply tension, the material stretches slightly and exerts a restoring force that balances the tension. The result is a new state of equilibrium. Similarly, if you apply compression, it gets shorter, exerts a restoring force and reaches equilibrium. However, if you apply tension to a material with "negative compressibility", the material responds by shrinking slightly, which increases the tension further, which causes it to shrink more. The logical consequence is that a slight applied tension would cause such a material to collapse and a slight applied pressure would cause it to explode. Such a material could clearly not exist.

But now Zachary Nicolaou and Adilson Motter at Northwestern University have found a little wiggle room in which such a material could exist. While they acknowledge the impossibility of a material having a continuous negative compressibility, they believe it should be possible to manufacture materials with negative compressibility at a particular point – allowing seatbelts to tighten up suddenly in the event of a car crash, for example. The trick is to design a material with two metastable structural configurations, one more compact than the other. The desired response would occur if the material could jump into the more compact state if the tension is increased beyond a particular value. Despite these bizarre requirements, the researchers have used molecular dynamics simulations to establish that such materials are indeed physically plausible.

Parallel with traffic

Motter is an expert on the physics of complex systems and networks, and draws a parallel with a famous paradox in traffic management – the removal of an intermediate road can actually reduce congestion by distributing traffic more evenly around the remaining roads, changing the traffic pattern from a "series" to a "parallel" one. "This is analogous to the system we are studying," explains Motter, "to the extent that the constituents of the material are made up of four particles. When you apply tension, this causes the inner particles to decouple from each other – it's like breaking a bond. That causes the outer particles to be more strongly attracted to each other – basically going from a series configuration to a parallel one. This causes the material to contract".

That's the theory, but Motter is also optimistic that such a metamaterial could actually be made. "The most straightforward approach would be to use elements that have spring-like behaviour, such as rubber," he says. "Depending on how you assemble together little pieces of rubber, you could have a material that behaves in the way we are proposing here."

"Interesting applications"

Nanoscientist Ping Sheng at Hong Kong University of Science and Technology, whose research group has developed materials that show negative compressibility in response to sinusoidal forces, says "The novel point about this work is that it proposes negative compressibility at zero frequency, i.e. with steady forcing. Such a system could still be stable because it would involve stored energy."

He concludes, "I would be interested in seeing a physical realization of what has been proposed. That may indeed have some interesting applications."

The research is published in *Nature Materials*.

About the author
Tim Wogan is a science writer based in the UK