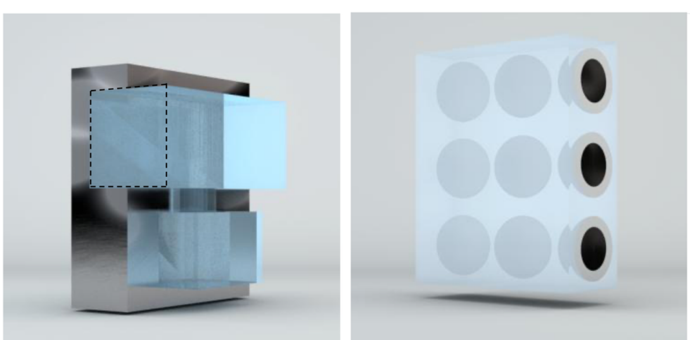
No Free Lunch for Sound Waves

Sound wave scattering can be increased in one frequency range only by reducing scattering in another range, according to experiments—a discovery relevant for acoustic engineering.

By **Mark Buchanan**

Acoustic metamaterials allow blocking, absorbing, or redirecting waves in ways not possible with conventional materials. Now researchers have shown that all such structures face a previously unrecognized constraint: The total acoustic scattering is fixed, so that boosting scattering in one frequency band necessarily depletes it elsewhere [**1**]. This general restriction provides a new way of thinking about how acoustic performance can be optimized, which could guide the design of broadband sound-control devices, from noise barriers to acoustic cloaks.

By building structures into materials on length scales smaller than the wavelength of sound, researchers can create artificial resonant elements that interact strongly with acoustic waves.



Acoustic guinea pigs. Researchers used numerical simulations and experiments to test a new rule for sound waves. The simulations involved acoustic waves propagating through water and scattering from two different resonators—a Helmholtz resonator (left) and a lead-core resonator of periodic construction (right).
Credit: S. Qu et *al.* [**1**]

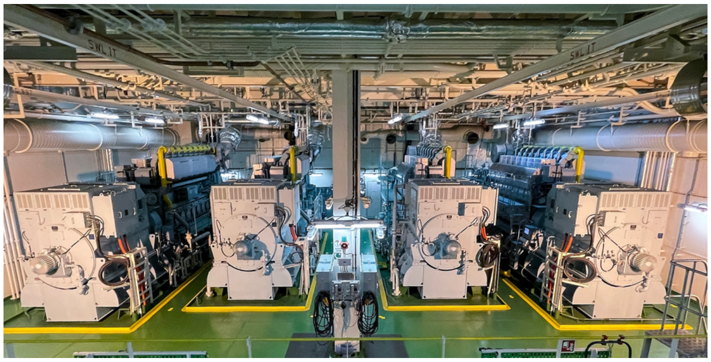
Such structures can produce effects that are difficult or impossible to achieve otherwise—for example, strong sound attenuation through thin material layers. Such advances have led to new techniques for lightweight soundproofing and sound steering.

Yet metamaterial engineering also faces trade-offs. Material designs typically rely on resonances, which influence sound in a narrow frequency band. Building complex structures to shape performance over a wide spectrum remains an important challenge, says acoustics engineer Nicholas Fang of the University of Hong Kong. He and other researchers in the field remain uncertain about whether fundamental limits govern how scattering can be distributed across all frequencies.

“Our work started with a simple curiosity,” he says. “When you design an acoustic metamaterial, does improving performance in one frequency range inevitably force a penalty somewhere else?”

In pursuing this question, he and his colleagues found inspiration in nuclear physics. In the 1960s, physicists scattered high-energy photons from atomic nuclei to probe their internal structures. One general rule they found—called the Baldin sum rule—states that a nucleus has a fixed “budget” for scattering photons. That total is set by two intrinsic properties of the nucleus called the electric and magnetic polarizabilities. These parameters describe how the nucleus distorts in the presence of external fields. According to this rule, if a nucleus scatters more in some range of frequencies, it must necessarily scatter less in some other frequency range.

Fang and colleagues have now shown that an analogous



Reducing the cacophony. As acoustic engineers attempt to reduce noise in environments like this engine room of a liquified natural gas ship, they may need to be aware of the newly discovered limitation on acoustic scattering.
Credit: Ирина Старикова/stock.adobe.com

relationship holds for acoustic metamaterials. To do so, they started from a mathematical result of wave physics called the optical theorem, which expresses the conservation of energy. Any wave hitting a material must either be absorbed by the material, transmitted forward, or reflected backward. Using principles of linear wave theory, the researchers derived a general expression for the total acoustic scattering across all frequencies. In analogy with the Baldin sum rule, they found that the total scattering is equal to a quantity that depends only on the material's mass density and compressibility. "The rule turns out to be surprisingly clean," Fang says.

To check their result, the researchers ran numerical simulations of sound waves in water interacting with two metamaterial structures designed to strongly affect passing waves. In both cases, they found confirmation of the acoustic sum rule. The team also ran experiments with resonant structures in air, further confirming the rule. Fang says that it was important to test two systems with different acoustic properties in order to better demonstrate the wide applicability of their theoretical prediction.

The physical implication is striking, Fang says. Rather than being freely adjustable, the overall budget for scattering is fixed—designing for more scattering in one part of the spectrum means having less scattering elsewhere.
"This is an amazing discovery," says metamaterials expert Yuri Kivshar of the Australian National University. "This observation calls for deeper studies of acoustic metamaterials based on the fundamentals of wave physics and holds promise for developing new techniques for designing sound-control devices."

Along those lines, Fang and colleagues suggest that their framework could provide a unifying foundation for the design of acoustic devices with optimized broadband performance. "It suggests that engineers should think across all frequencies from the start," Fang says. For example, to suppress an engine's 200-Hz "hum," a reduction in scattering might be required. But then "you must accept where that scattering budget will be reallocated—perhaps to higher frequencies," he says. "We hope this [principle] leads to more intentional designs rather than design by trial and error."

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REFERENCES

1. S. Qu *et al.*, "Acoustic analogy of quantum Baldin sum rule for optimal causal scattering," **Phys. Rev. Lett. 136, 226902 (2026).**