First-ever simulation of chaotic sound wave propagation confirms acoustic turbulence theory

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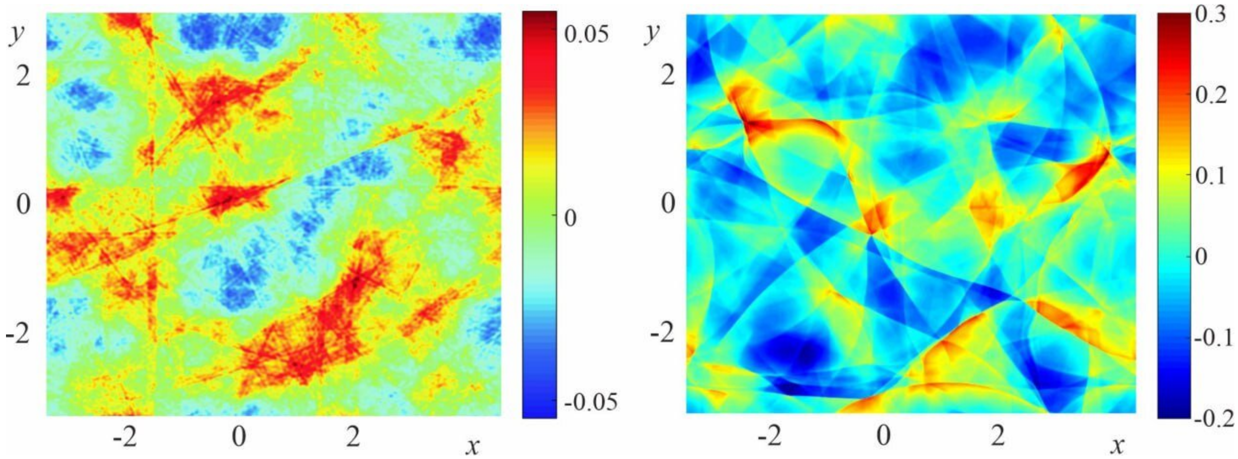

Gas density in the weak turbulence regime with small-amplitude sound waves (left) and in the strong turbulence regime with acoustic turbulence represented by a set of random shock waves (right). Credit: Evgeny Kochurin

Researchers have pioneered the use of parallel computing on graphics cards to simulate acoustic turbulence. This type of simulation, which previously required a supercomputer, can now be performed on a standard personal computer. The discovery will make weather forecasting models more accurate while enabling the use of turbulence theory in various fields of physics, such as astrophysics, to calculate the trajectories and propagation speeds of acoustic waves in the universe.

The research was published in *Physical Review Letters*.

Turbulence is the complex chaotic behavior of fluids, gases or nonlinear waves in various physical systems. For example, turbulence at the ocean surface can be caused by wind or wind-drift currents, while turbulence of laser radiation in optics occurs as light is scattered by lenses. Turbulence can also occur in sound waves that propagate chaotically in certain media, such as superfluid helium.

In the 1970s, Soviet scientists proposed that turbulence occurs when sound waves deviate from equilibrium and reach large amplitudes. The theory of wave turbulence applies to many other wave systems, including magnetohydrodynamic waves in the ionospheres of stars and giant planets, and perhaps even gravitational waves in the early universe. Until recently, however, it has been nearly impossible to predict the propagation patterns of nonlinear (i.e., chaotically moving) acoustic and other waves because of the high computational complexity involved.

Researchers from Skoltech, the Institute of Electrophysics of the Ural Branch of RAS (Yekaterinburg) and the Lebedev Physical Institute of RAS (Moscow) were the first to find a numerical solution to the equation describing the propagation of sound waves in turbulence, thus proving the theory proposed by Soviet scientists.

The researchers found solutions to several parts of the equation that mathematically describe the propagation of sound waves using parallel computing on four graphics processors (graphics cards) installed on the same computer. Instead of using a huge and very expensive cluster of computers—a supercomputer—that could provide an approximate answer, the team ran the simulation and arrived at an exact numerical solution using a small personal computer.

To verify their solution, the researchers simulated the propagation of sound waves in a nonlinear medium similar to superfluid helium at about -270°C. Under these conditions, helium becomes a superconducting quantum superfluid that can be used in superconductors—an essential element of quantum computers, maglev trains (in China and Japan), and many other high-tech devices. Superfluid helium is also used in the nuclear power industry.

The theory of turbulence confirmed for sound waves is an important discovery similar to the periodic table, where the theory of wave turbulence represents the table and each type of turbulence (acoustic, gravitational, magnetohydrodynamic) is an individual element whose properties are fully described by its position in the table and accurately predicted by the theory.

The theory of turbulence can be applied to any wave system, such as ocean waves: the numerical solution of these equations has been incorporated into global weather forecasting and climate change models, making weather forecasts more accurate.

"Elucidating the nature of turbulence is one of the most important open questions in modern physics. Weather forecasting has become more accurate thanks to the development of turbulence theory. We plan to study other wave systems, such as large-amplitude ocean waves.

"Surprisingly, sound waves and ocean waves have a lot in common: for example, the breaking of large-amplitude ocean waves is similar to the formation of an acoustic shock wave. Wave breaking results in high energy or pressure densities. There is a hypothesis that turbulence is caused by such collapses of different nature," explains Evgeny Kochurin, a member of the project team.

Kochurin is a research scientist at the Laboratory of Integrable Systems and Turbulence at the Igor Krichever Center for Advanced Studies at

Skoltech and a senior researcher at the Nonlinear Dynamics Laboratory at the Institute of Electrophysics of the Ural Branch of RAS.

More information: E. A. Kochurin et al, Three-Dimensional Acoustic Turbulence: Weak Versus Strong, *Physical Review Letters* (2024). DOI: 10.1103/PhysRevLett.133.207201. On *arXiv*: DOI: 10.48550/arxiv.2407.08352

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