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A swinging showerhead leads to discovery of a new mode of vibration in nature

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During the hot summer of 2020, confined to his Pasadena home during the COVID-19 pandemic, National Medal of Science-winning applied physicist Amnon Yariv took frequent and long showers to cool off. A surprising result, to go with his record-breaking water bill, was a proposal and theoretical model for a new class of vibrations that can convert a constant force, such as wind or water, to a mechanical oscillation.

It wasn't exactly a eureka moment. The thought did not come all at once in the bathtub, a la Archimedes. But it was in the shower that Yariv first noticed something unusual about the way the water-spraying showerhead behaved when left dangling by its hose. To Yariv—a scientist who has been studying waves and their properties for most of his 70-plus-year career—that showerhead was more than just a fixture on a flexible tether spraying water at the wall. It was part of an oscillating system.

Oscillations are the rhythmic, or periodic, variations in the world around us. The ebbing and flowing of the sea is an oscillation. The vibrations of a plucked guitar string are oscillations. Even light is an oscillation, according to quantum theory.

Yariv observed that as he increased the water flow in the shower, the system began to behave unexpectedly. In fact, he saw a bimodal, joint oscillation—two different oscillations synchronized with each other. While the shower head was swinging back and forth like a pendulum, it was also twisting in sync in one direction and then the other. It was clear that those two oscillatory modes were driving each other since a damping of one would immediately cause the other mode to cease oscillating.

What's more, Yariv saw that the joint oscillation was predictably unstable. Once a certain threshold of water pressure was reached, the oscillation kept increasing in amplitude even when the water flow remained constant.

"This bimodal oscillation is like an Argentinian tango, where each dancer has to remain completely in sync with the other or else they stumble on each other," says Yariv, the Martin and Eileen Summerfield Professor of Applied Physics and Electrical Engineering. "The idea that a steady force can be used to excite this kind of entangled bimodal oscillation has never been proposed nor demonstrated."

Yariv spent the next few years working out the mathematical model explaining what he had observed during those hot summer months. The mathematics underlying Yariv's two-mode model, which he nicknamed "Yariv's groove," constitutes a sweeping extension to two modes of a model of a single mode oscillation proposed by the physicists Michael Faraday and Lord Rayleigh a century and a half ago.

Yariv's new paradigm could have implications in fields ranging from civil engineering to quantum electronics. For example, one possibility lies in harnessing the essentially limitless energy of wind. However, Yariv cautions that since the bimodal oscillations described in the new work become increasingly intense once the driving force (wind, here) reaches a threshold, a way to control that instability would be required.

That instability also points to factors that should be considered when constructing structures such as buildings and bridges, to prevent this type of oscillation from getting out of hand and damaging or completely destroying them.

Oscillations, an introduction

To understand the new paradigm that Yariv suggests, it is helpful to first consider a classic example of an oscillation mode, say a child on a swing. Described in physics terminology, the child and the swing are a system. If the child is young, another person is required to push them periodically, usually once per swing or once every few swings. Otherwise, the child will eventually stop swinging due to friction.

"It turns out that almost all oscillations in nature have a periodic force driving them," says Yariv.

As the child gets older, they might learn to keep the motion going without the pushing parent. They do that by pumping their legs forward and backward, or if standing, by pulling their weight up and down on the swing's chains. In both cases, the child is effectively modulating, or varying periodically, a parameter of the system (the moment of inertia in the first case and the weight of the child as experienced by the swing seat in the second). The modulation rate in both cases is twice that of the swinging frequency.

Such "parametric" pumping of oscillations was observed by Michael Faraday and explained mathematically some 50 years later, in 1883, by Lord Rayleigh.

"That work by Lord Rayleigh laid the foundation for parametric physics, which, in the field of nonlinear optics, has become one of the most exciting branches of modern physics and a major activity in the departments of applied physics and physics at Caltech over the last 50 years," says Yariv.

Back to the shower

Yariv conjectured that such parametric oscillation was behind the bimodal oscillation he observed in the dangling showerhead's behavior. But here, rather than an external agent modulating a parameter—the mass, the gravitational constant, or the moment of inertia—at twice the resonance frequency, Yariv saw that it was the entangled collaboration of two oscillation modes due to a system nonlinearity that was powering the oscillation by a constant unchanging force.

"What we have here is a cycle of excitation," says Yariv.

Once the showerhead begins its twisting, or torsional oscillation, the steady force of water pushing back perpendicularly to the face of the showerhead generates the periodic force that drives the pendulum excursion conventionally, once per cycle. That pendulum motion in turn modulates nonlinearly the torsional spring constant—here, the parameter, twice per cycle—thus generating internally what is called the second harmonic, needed per Lord Rayleigh, to drive the torsional oscillation, completing the cycle.

"My study only follows the system through the onset of the bimodal oscillation and into the early stage of the unstable oscillation, and stops before the heavy showerhead craters the wall," says Yariv. "But the new entangled bimodal oscillation is unstable. It doesn't reach a steady state. It keeps getting larger."

Implications far beyond the shower

The oscillation Yariv first took note of in the shower serves as a model system for a whole class of oscillations, and his mathematical analysis should apply to all members of that class, he says. Yariv points to other examples that very likely belong to the class. A stop sign fluttering on a windy day is one example. A more infamous example, he says, is very likely that of the 1940 collapse of a suspension bridge that spanned the Tacoma Narrows in Washington.

The bridge, nicknamed Galloping Gertie for the way it bucked and swayed in the wind, eventually collapsed during a windstorm in 1940. Videos of the bridge collapse show the roadbed undergoing vertical as well as transverse oscillations leading to the breakup. Some of the key features of the showerhead oscillation exist in both cases: bimodality, steady force threshold, and instability.

"The abundant occurrence of steady forces in nature will provide rich areas of investigation to identify bimodal oscillations which can be excited by these forces," says Yariv.

He notes that the mechanical motion generated by such bimodal oscillation could also be converted to rotary motion and, thus, to electric power generation. The finding could also have applications in optics, electronics, and cosmology, where Yariv says the bimodal oscillations could be related to the pre-merger dance between colliding black holes.

The paper describing Yariv's theory, "On a class of bimodal oscillations powered by a steady, zero-frequency force—Implications to energy conversion and structural stability," appeared in the September 11, 2023, issue of the journal *Proceedings of the National Academy of Sciences*. A commentary on the work by Demetrios Christodoulides of USC, appeared in the October 4, 2023, issue of the same journal.

More information: Amnon Zalman Yariv, On a class of bimodal oscillations powered by a steady, zero-frequency force—Implications to energy conversion and structural stability, *Proceedings of the National Academy of Sciences* (2023). DOI: 10.1073/pnas.2311412120

Demetrios Christodoulides, Dances of dual dynamics enable parametric oscillations under a steady force, *Proceedings of the National Academy of Sciences* (2023). DOI: 10.1073/pnas.2314442120

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