QUICK STUDY

Kasper van Wijk is an associate professor and **Sam Hitchman** is a PhD candidate in the department of physics at the University of Auckland in New Zealand. Both are affiliated with the Dodd–Walls Centre for Photonic and Quantum Technologies.

Apple seismology

Kasper van Wijk and Sam Hitchman

Just as an earthquake's seismic waves reveal properties of Earth's interior, elastic surface waves on an apple can tell us about what's going on inside the fruit.

An apple, like Earth, has a core at its center and a thin skin on the outside. In between is the apple's flesh, equivalent to Earth's mantle. Of course, a more careful comparison would uncover important differences between those spheroidal objects. For example, seismic waves reveal that Earth's core is made of a liquid outer core and a solid inner core, whereas the apple core contains seeds that can be surrounded by air. The full interior of our planet cannot be directly sampled, so its properties must be inferred from indirect measurements, such as of seismic waves. An apple can be sampled as a whole, but typically the process destroys the apple. We and our colleagues are developing apple seismology as a nondestructive alternative to monitor the freshness and other properties of the fruit. Our work is still in its early stages, but we hope to continue to refine our techniques to develop a method that is competitive in cost, speed, and reliability with conventional techniques.

Wave propagation

On 11 March 2011, seismic stations around the globe recorded ground displacement due to seismic waves excited by the devastating Tohoku earthquake in Japan. The zigzag pattern in the left panel of figure 1 represents the recordings of seismic surface waves during the waves' four-hour round-trip from the earthquake origin to its antipode and back. Because the round-trip distance is about 40 000 km, those surface waves traveled at roughly 3 km/s. The second lap of the surface waves is also visible in the panel, but it is less prominent because seismic waves scatter and dissipate energy during their journey. Such surface waves yield important contributions to the current understanding of the depths of our planet that cannot be sampled via drilling.

A similar pattern in the right panel of figure 1 represents elastic waves on the surface of a Braeburn apple. The applequakes we measured were generated via thermoelastic expansion of the apple after a short pulse of laser light heated a small spot on the surface. We used a laser Doppler vibrometer to record laser light reflected off the apple's surface. As applequakes perturb the fruit's surface, the reflected light is Doppler shifted by an amount proportional to the speed of the perturbation. We found that surface waves take a bit less than 3 ms to travel around an apple with a circumference of 235 mm, so the speed of the elastic waves is about 100 m/s. The apple also supports compressional waves, longitudinal waves analogous to sound waves. Those are weaker than the elastic waves, and they travel at about 140 m/s, less than half the speed of sound in air. And even though the apple is 80% water by weight, that speed is an order of magnitude below the speed of sound in water. Intercellular spaces filled with air in the apple are responsible for slowing the compressional waves; a similar effect occurs in water with air bubbles, where the speed of sound is slower than in either water or air. The apple's structure also leads to strong wave dissipation. The wave amplitude decay per cycle is an order of magnitude greater in the apple than in Earth; indeed, the second lap around the fruit is barely evident in figure 1.

Normal modes

The interference of propagating waves on guitar strings or saxophone windpipes can result in standing waves. The interference of propagating waves in a body such as an apple or Earth also results in standing waves, whose distinct patterns of motion are called normal modes. Destructive interference leads to nodes, locations where the amplitude of vibration is zero; constructive interference yields high-amplitude antinodes.

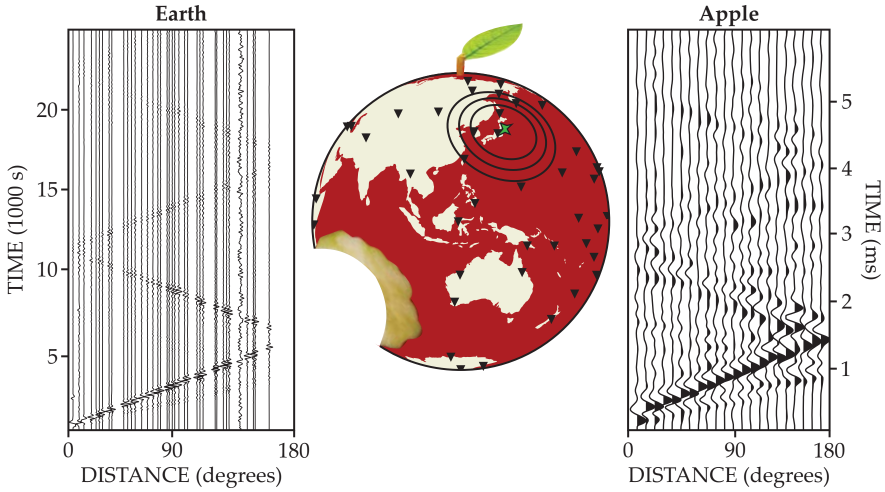

FIGURE 1. SEISMIC WAVES in a spheroid. Stations indicated by triangles in the central panel recorded seismic waves created by the 2011 Tohoku earthquake in Japan. The resulting waveforms are shown to the left. Distance is measured from the origin of the quake. The right panel shows "seismic" waves recorded after a Braeburn apple was excited by a short laser pulse.

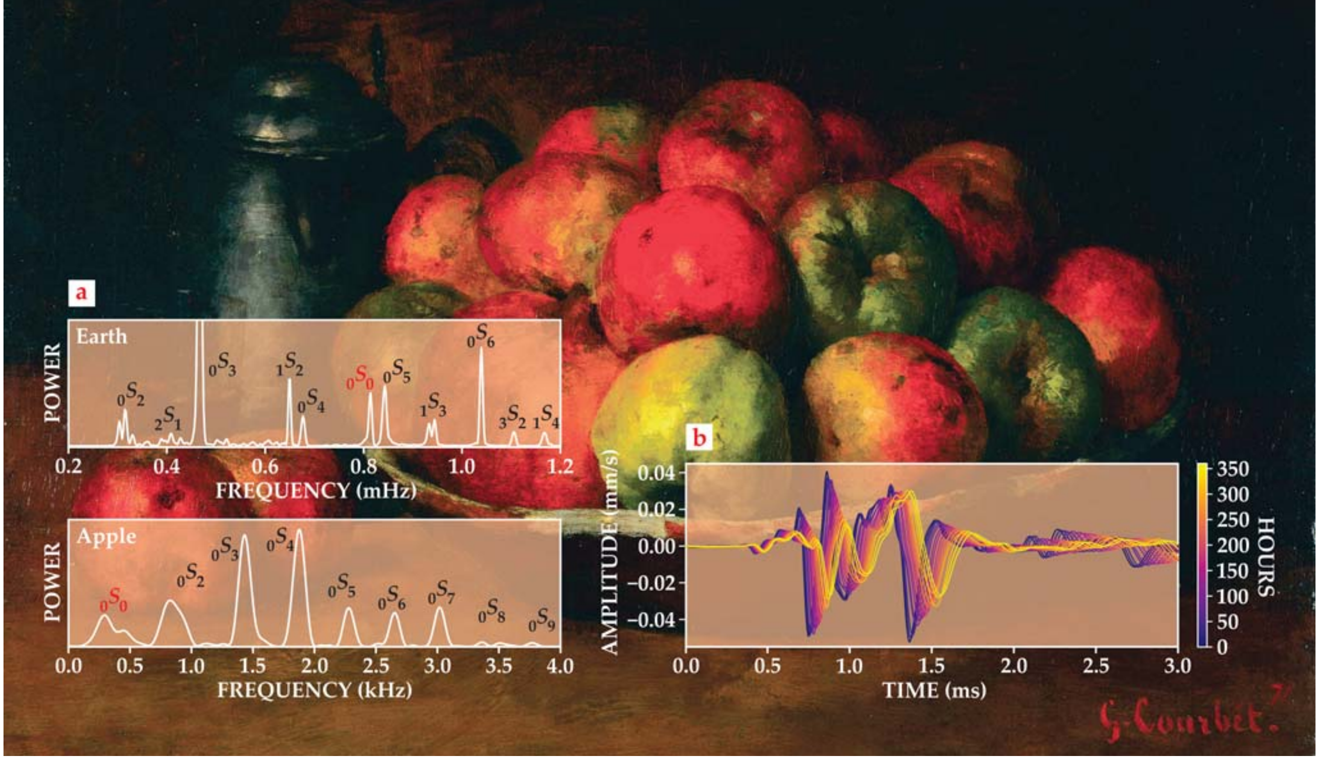

FIGURE 2. NORMAL MODES, NORMAL AGING. Peaks in the power spectral density **(a)** reveal the normal modes of vibration for Earth and an apple, which are analogous to a musical instrument's harmonics. Subscripts describe the nodal structure of the modes. Power is given in arbitrary units. **(b)** Wave fields in an aging apple (color bar) show that the amplitude and propagation speed fall as the apple loses freshness. (Background: *Still Life with Apples and a Pomegranate*, Gustave Courbet, 1871.)

In solids, the so-called spheroidal modes, typically denoted by an "S," represent radial particle motion. Subscripts define the number of longitudinal and latitudinal nodal lines—that is, lines of zero displacement. The fundamental spherical mode, $_0S_0$, is an in-and-out breathing of the volume as a whole and contains no nodal lines. The $_0S_2$ mode, with zero longitudinal and two latitudinal nodal lines, makes the body resemble a rugby football alternately aligned with the poles and the equatorial plane. Modes with larger values of n vibrate at higher frequencies and sample regions closer to the surface than do the low-n modes.

The top panel of figure 2a shows an estimate of the power spectral density of the Tohoku earthquake's seismic waves, as recorded at station ANMO in New Mexico. Each peak corresponds to a normal mode whose annotation is based on a calculation assuming a spherical Earth. The bottom panel of the figure displays the power spectral density of the wave field 170° from the source of the quake in our Braeburn apple. Here, the peak labels are based on normal modes computed for a homogeneous sphere whose elastic properties are derived from the average density, surface-wave speed, and compressional-wave speed in the apple. Note that resonant modes in the apple have frequencies in the kilohertz range, whereas Earth resonates with millihertz frequencies. The six orders of magnitude separation in frequency reflects the different ratios of size to wave speed for the two objects.

The observed resonant modes in Earth and the apple align reasonably well with those predicted by spheres with suitable average properties. The differences in the Earth and apple mode spectra highlight important differences in the bodies' internal structures. Earth's breathing mode $_0S_0$ is at a higher frequency than its football mode $_0S_2$ because wave speeds in Earth generally increase with depth. The lowest frequency resonance in the apple is the breathing mode $_0S_0$, which senses the lower-than-average wave speeds in the apple's core. In addition, the higher-frequency $_0S_2$ mode is broader and slightly offset compared with the best-fitting peak predicted with homogeneous spheres; the discrepancies confirm that the elastic properties of an apple vary with depth.

As an apple ages

From our "seismic analysis" of waves in an apple, we can estimate average elastic properties. Young's modulus, for example, is closely related to the firmness index, a commonly used parameter in the apple industry to quantify apple firmness. With the laser source and receiver fixed to be 170° apart, we recorded the wave field in our apple every day for 15 days. Figure 2b reveals two trends associated with the aging of the apple. First, amplitude decays steadily with age. Second, as the apple ages, the wave arrival time increases monotonically. Those two effects show that the apple loses firmness with age; indeed, during our 15-day trial, Young's modulus decreased by about 19%. It is also clear, however, that the amplitude effect has more analytic power. Over the course of our experiment, the amplitude of the surface waves dropped by a whopping 75%.

Additional resources

▶ J. R. Cooke, R. H. Rand, "A mathematical study of resonance in intact fruits and vegetables using a 3-media elastic sphere model," *J. Agric. Eng. Res.* **18**, 141 (1973).

▶ C. B. Scruby, L. E. Drain, *Laser Ultrasonics: Techniques and Applications*, Adam Hilger (1990).

▶ S. Stein, M. Wysession, *An Introduction to Seismology, Earthquakes, and Earth Structure,* John Wiley & Sons (2013).

▶ S. Hitchman, K. van Wijk, Z. Davidson, "Monitoring attenuation and the elastic properties of an apple with laser ultrasound," *Postharvest Biol. Technol.* **121**, 71 (2016).