Low-noise, mechanical, monolithic seismic sensors

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Very sensitive, tunable, and scalable sensors for low-frequency seismic-noise detection can be configured as both seismometers and accelerometers.

The need for low-noise, low-frequency, wideband, high-resolution seismic sensors (such as seismometers and accelerometers) is increasing for both scientific and industrial applications. Seismometers are required, for instance, in geophysics for environmental monitoring, seismic-noise studies (including analysis of seismic risk and early-warning systems), and control of interferometric gravitational-wave detectors. In industry, these devices are needed for civil applications related to the characterization and stabilization of oscillating structures, including buildings and bridges.

Their development is still a major challenge today, because—for a number of historical and technical reasons—sensors have thus far often been produced that do not have the dimensions, frequency bands, costs, or sensitivities that are compatible with their key applications. In fact, the size and weight of current-generation seismic sensors prevent their extensive and effective use in many scientific and industrial applications. In particular, there are currently no sensors (either seismometers or accelerometers) of reasonable, useful size for industrial applications in the frequency range from micro- to millihertz.

We developed a monolithic, tunable, folded-pendulum sensor (see Figure 1), shaped using precision and electric-discharge machining. The device is configurable as both seismometer and—in a force-feedback configuration—accelerometer. Its main aim is to monitor the horizontal degrees of freedom. The sensor is very compact (140 × 134 × 40 mm³), but it is characterized by a very low resonance frequency (down to 70 mHz) and the device is very sensitive at low frequencies (from ~10⁻⁶ to 10 Hz).

Specific resonance frequencies and the sensor’s tunability range, as well as its dimensions and weight, can be defined in the design phase. The device’s monolithic folded-pendulum configuration makes its fully tunable from 70 to 720 mHz. The readout system (which, combined with the choice of resonance frequency, determines the sensor’s sensitivity) can be an optical lever and/or an interferometer. The interferometric readout option and its mechanical characteristics make our new sensor the most sensitive device of its size developed to date, with a sensitivity of 10⁻¹² m/Hz¹/² in the operational range from 10⁻¹ to 10 Hz.

Figure 2 shows the resulting sensitivity curves for a seismometer configuration with optical levers (equipped with position-sensitive photodetectors and quadrant photodiodes), as well as interferometric readouts in air without thermal stabilization. We also show the Peterson new low-noise model, i.e., the minimum earth noise evaluated from a collection of seismic data from 75 sites around the world. Monolithic seismometers are already operational at a small number of sites, both to acquire seismic data for scientific analysis and to evaluate their performance at very low frequencies (10⁻⁶–10⁻³ Hz). At present, two mechanical, monolithic horizontal sensors are located in a dead-end side tunnel, 2000 ft deep in the Homestake mine in South Dakota, Continued on next page
Figure 2. Theoretical and experimental sensitivity curves of our monolithic seismometer with optical-lever and laser-interferometric readouts. PSD: Position-sensitive photodetector. NLNM: New low-noise model. STS2: Streckeisen-2 seismic sensor.

Figure 3. Sensitivity curves of the monolithic accelerometer with optical-lever and laser-interferometric readouts.

In conclusion, these sensors can be used in any application requiring movement measurements. Their applicability is significantly enhanced compared to older sensors because of their portability and light weight (<1kg). We are currently developing more sensitive mechanical sensors, including ones that detect changes in vertical (or any angular/tilt) degrees of freedom, through a scientific-technical collaboration with a team at the Galli & Morelli factory (Acquacalda, Lucca, Italy). We are also developing specific sensor designs for scientific and industrial applications, some of which are part of national and international research collaborations.

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References

where the Deep Underground Science and Engineering Laboratory is located.

When equipped with a suitable feedback system, our new sensor behaves like an accelerometer. We show three sensitivity curves (in air without thermal stabilization) corresponding to optical levers and interferometer readouts in Figure 3. In this configuration, the sensitivity is better than $10^{-11} \text{m/s}^2/\text{Hz}^{1/2}$ for frequencies from $10^{-3}$ to 10Hz.