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Research and Development Status of a New Rotational Seismometer Based on the Flux Pinning Effect of a Superconductor

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Abstract Rotational motions induced by earthquakes are expected to contain unique geophysical information not obtainable from translational motions, such as the distribution of slip velocity near the earthquake source. However their observations have not been performed as actively as those of translational motions, mainly because of technical difficulties. Rotational seismometers with sufficient resolution (better than 10^{-10} rad/sec /Hz$^{1/2}$ over 0.1 mHz to 10 Hz) and reliability at reasonable cost are needed to establish broad observation networks for rotational seismology. To achieve this goal, we are developing a seismometer with a new design based on a proof mass levitated by a magnetic suspension that uses the flux pinning effect of a superconductor to make it freely rotatable without introducing unwanted parasitic resonances and other complexities. Prototype systems were built and tested to assess the feasibility of the technologies used in the new seismometer, and their advantages and capabilities have been successfully demonstrated. The design of the new seismometer together with the status of the development and future plans are presented in this article.

Introduction

Ground rotational motions induced by local and teleseismic earthquakes or volcanic activity are thought to contain important and unique information related to rupture or eruption processes (Aki and Richards, 2002). For instance, in the last decade, a theoretical model that indicates intense and observable rotational motions coupled to the large variation of slip velocity on the fault plane was studied. It was demonstrated that one can estimate the spatial variation of the slip velocity from the rotational motions observed near the fault (Takeo and Ito, 1997; Takeo, 1998). Earth's dynamics, such as Chandler wobble, tidal friction, and rotation of the plate dynamics, would be better understood if rotational motions on the order of 10^{-15} to 10^{-14} rad/sec were observed directly (LePichon, 1968). In addition, if true rotational motions are observed, the signals of translational seismometers can be corrected by removing contaminations due to rotational motions, and we can improve the precision of inversion analyses.

Despite these motivations, few observations of rotational ground motion have been successfully performed, while translational motions are actively and routinely observed with traditional and commercially available seismometers. It should be especially noted that the observations using the global seismometer networks have lead to a deeper understanding of various phenomena in the geosciences. Thus, it is desirable to build such networks for rotational motions as well. One major reason for the lack of rotational information is that the rotational motions have been considered too small to observe with the available technologies. Commercial rotational sensors that employ traditional detection techniques like gyroscopes with mechanical rotators, piezoelectric materials, or a liquid as an inertial reference are suitable for use in observation networks. However, their resolutions are typically worse than 10^{-6} rad/sec^2 /Hz$^{1/2}$ below 100 mHz (Nigbor, 1994), and one can make scientifically significant measurements with these instruments only at locations near the source of the earthquakes. It is also possible to restore the rotational components of ground motions by obtaining the differences between signals of translational seismographs (Wiens *et al.*, 2005); however, the accuracy of this indirect detection method is technically limited, particularly in the higher frequency region (Suryanto *et al.*, 2006). On the other hand, much higher resolution has been achieved by the state-of-the-art ring laser gyroscope, directly observing teleseismic events (Igel *et al.*, 2005, 2007). The laser gyroscope technique has other advantages, but they require sophisticated facilities and complicated operation, which is not compatible with large-scale networks or mobile observations (Stedman, 1995).

With the new rotational seismometer proposed in this article, we attempt to fill the gap between the traditional sen-

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sors and laser gyroscopes. It is designed to realize sufficient resolution while maintaining the practical usability crucial for applications such as network and mobile observations (Igel *et al.*, 2007). Although there have been similar developments based on mechanical torsion balances (e.g., Cowsik, 2007), the key technology of our new instrument is a proof mass suspension that utilizes the flux pinning effect of a superconductor. Prior to the research and development (R&D) of the new rotational seismometer, we worked on a magnetic levitation system based on this technique to emulate the floating proof mass of an accelerometer used in space missions. During the experiments, we found that the floating mass behaves as a virtually free rotator about the single principal axis while rigidly constrained by the magnetic field in the other degrees of freedom (DoF). This implied that the floating mass could be ideal as a proof mass of a mechanical sensor for detecting rotational motion.

The details of the technology and the results of a feasibility study are described in the next sections.

Basic Design: Description of the New Rotational Seismometer

A schematic diagram of the proposed rotational seismometer is shown in Figure 1. A type-II high-Tc superconductor disk (Y-Ba-Cu-O, Tc ~ 90 K) is chilled by a cryocooler connected with a heat link that is specially designed to isolate mechanical vibration. A proof mass, housing a permanent magnet, is located below the superconductor. In the normal conducting state, the magnetic fluxes of the permanent magnet freely penetrate through the metal oxide. Once the metal oxide is sufficiently chilled by the cryocooler, and a superconducting state is achieved, fluxoids (quantized current vortices) will be established in the disk. The fluxoid movement is restricted by defects or impurities inherent in type-II superconducting materials. This phenomenon is known as the flux pinning effect. The pinned magnetic field stays where it is trapped and generates an attractive force that suspends the permanent magnet in the proof mass. The proof mass levitates at the equilibrium point as a result of this attractive force and other external forces due to Meissner effect and gravity. Because the principal axis of the permanent magnet is aligned vertically, it is in principle, free to rotate about the vertical axis. Hereafter, this article will refer to this rotation about the vertical axis as yaw. The rotational seismometer operates as a closed-loop sensor, transducers such as a laser interferometer, an electrostatic transducer, or an optical lever monitor the relative angle between the ground and the levitated proof mass. This is compensated by a servo system, which applies an adequate torque to the mass using electrostatic actuators. Neither the transducers nor the actuators have mechanical contact with the proof mass, which prevents unwanted disturbances from interfering with precision measurements.

The electrostatic actuator is shown schematically in Figure 2. A pair of conducting flag electrodes is attached to the proof mass, and two fork electrode pairs are attached to the outer frame (fixed to the ground) around the flag electrodes.

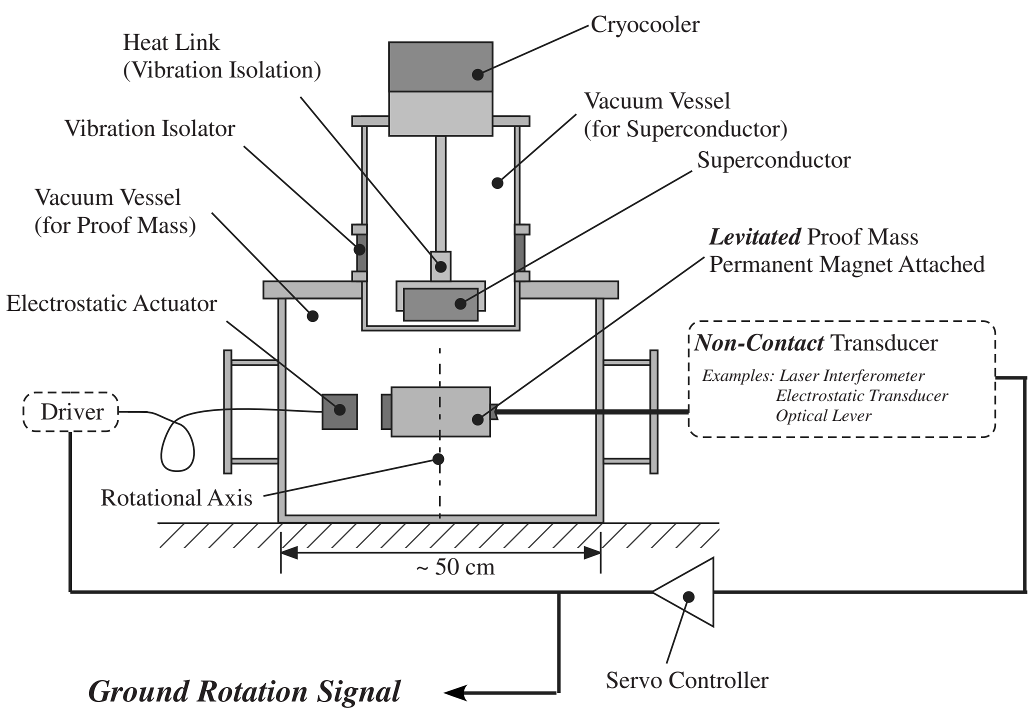

Figure 1. A schematic diagram of the new rotational seismometer (side view). A proof mass is levitated by the magnetic field pinned into the disk of the superconductor placed above the permanent magnet. Rotational motion of the mass is monitored and controlled by a non-contact transducer and electrostatic actuators. The system works as a closed-loop seismometer.

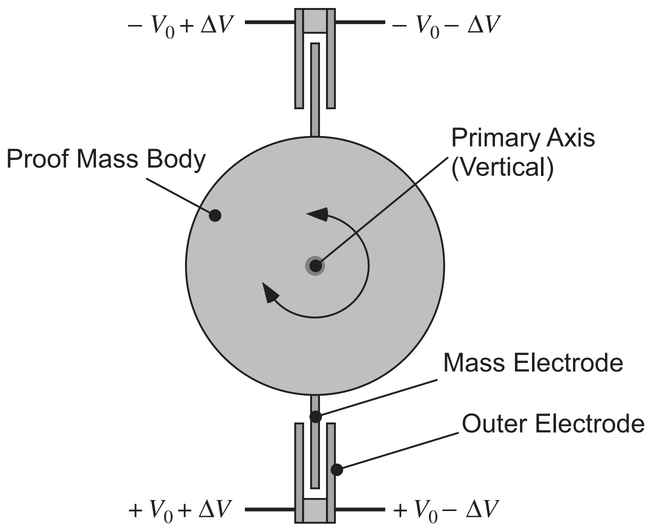

Figure 2. Fully noncontact electrostatic actuators that control the rotational motion of the proof mass (top view).

When a bias voltage ($\pm V_0$) is applied to both electrodes on each fork (with opposite signs for the two forks), the flag electrodes on the mass charge accordingly. By applying a differential voltage (ΔV) on the sides of each fork, one can generate an electrostatic force on the flag electrodes that applies a torque to the proof mass. This type of actuator can generate relatively small forces. An actuator efficiency of only 18 nN/V is estimated for electrodes with an area of 4 cm^2 and a separation of 4 mm between them for a bias voltage of 80 V. It should also be noted that the actuator is nonlinear, as the generated force is inversely proportional to the square of their separation. If needed, one can improve the actuation efficiency and linearity by applying a bias voltage between the moving and fixed electrodes (Touboul *et al.*, 1999), but this would require a wire connection between the floating mass and the ground, which degrades the free rotation of the floating mass. Because a linear signal can be obtained as long as the mass is maintained at a defined locking point, we adopted the nonlinear actuator for simplicity. This was one of the issues to be proven in our test experiments.

A superconducting magnetic suspension has several advantages. As long as the metal oxide disk is kept in a superconducting state, the proof mass is suspended completely passively, whereas magnetic suspension systems using nonsuperconducting magnets require continuous active control just for stable levitation (Earnshaw's theorem). This simplifies the system substantially and allows highly reliable and robust operation. The advantages resemble those of superconducting gravimeters over mechanical instruments (van Dam and Francis, 1998). Because the magnetic suspension has no restoring force in the yaw direction, in principle, an infinite natural period could be achieved in this DoF. This is a crucial advantage to improve the resolution at low frequencies. Very long natural periods can be achieved using sophisticated torsion balances or other traditional mechanics (Cowsik, 2007, Schlamminger *et al.*, 2008), but they inevitably suffer from internal resonances of the suspension wire. As there is no elastic element in the magnetic suspension, no internal parasitic resonance of the mechanical components exist, which may couple to and disturb the yaw motion. This is also helpful in simplifying servo design. Some practical limitations may be expected from the magnetic suspension as well. For instance, the natural period could be limited due to asymmetry of the magnetic field, just as mechanical asymmetry limits the performance of traditional systems. External magnetic fields (e.g., earth magnetism) could cause long-term drift of the rotator. These effects have not been evaluated and will be studied in the future.

Status: Experiments for Feasibility Study

To assess the feasibility of the magnetically levitated rotational seismometers, we conducted experiments using two different setups: a model (prototype-1) to study the controllability of a floating proof mass with the fully noncontact electrostatic actuators shown in Figure 2 and a second model (prototype-2) with optimized design as a rotational sensor implemented with a nonmechanical cryocooler to reduce vibration noise.

Prototype-1

Prototype-1 was originally built as a ground simulator of a spacecraft accelerometer (Fig. 3). The proof mass was located above the superconductor and supported by the pinned magnetic field from below, that is, the system's topology was the same as that shown in Figure 1 but vertically inverted. The proof mass body was made of a glass–epoxy box containing a cylindrical permanent Neodymium (Nd) magnet. Motions of the levitated mass in all DoFs were monitored and controlled by a set of reflective phototransducers and electrostatic actuators that work with mirrors and electrodes

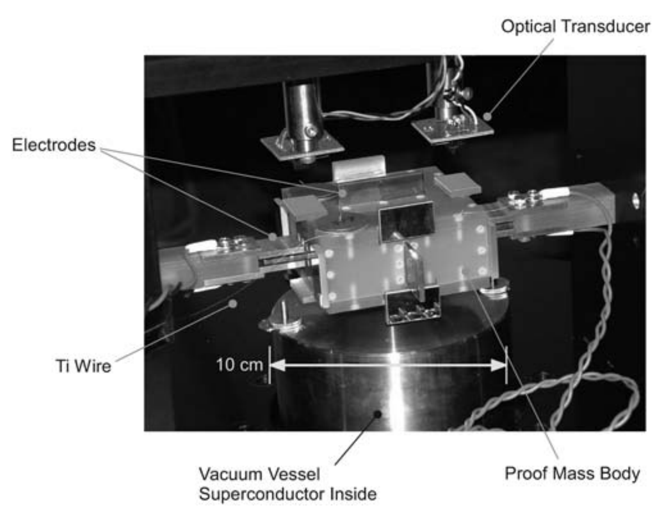

Figure 3. Prototype-1 built as a ground simulator for a spacecraft accelerometer.

attached to the side of the mass. Sensing and actuation were performed without mechanical contact, but the mass was loosely connected to the ground via two 0.1 mm diameter titanium wires. The support wires were necessary to keep the proof mass within the working range of the optical transducers and electrostatic actuators in all six DoFs, but they conferred a resonance at about 200 mHz in yaw. This obviously spoiled the advantage of the floating mass as the proof mass of a rotational sensor particularly at low frequencies, but the compromise was accepted because the main focus of the experiment was to demonstrate the controllability of the mass position with the weak nonlinear electrostatic actuators. Because the feedback force required to control the position of the proof mass against the ground acceleration is independent of the existence of the support wires, the capability of the actuator could be demonstrated even with the wires attached.

The superconductor disk was directly connected to and cooled with a Gifford–McMahon (G–M) cryocooler. G–M cryocoolers are widely used in many applications because they are simple and capable of cooling large volumes although at the cost of a relatively strong vibration. The mass was shaken intensively during cooling. Despite the large disturbances, the motions of the floating mass were successfully controlled (suppressed) in the yaw and horizontal DoFs with paired electrostatic actuators with 4 cm^2 area electrodes, using a bias voltage of 75 V. Figure 4 shows the transient of the error and control signals from free to controlled states in yaw. One can clearly see that the mass was brought instantly to the locking point once the feedback force was applied. Because mass control was achieved, it was concluded that the electrostatic actuators have sufficient capacity to control the free proof mass. This measurement was taken while the superconductor remained in superconducting state, and the cryocooler was turned off to eliminate its vibration.

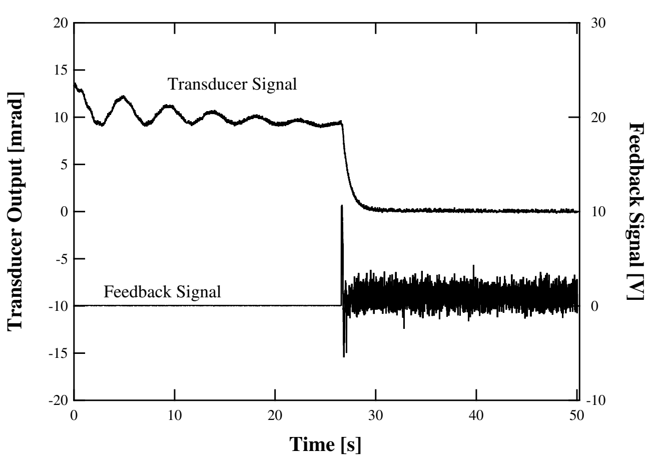

Figure 4. Transient of the proof mass angular motion (optical transducer signal) and applied torque (feedback signal). The fully noncontact electrostatic actuators are capable of keeping the proof mass position at the locking point against ambient disturbances.

Although the mass was not completely free because of the presence of the support wires, the system could be regarded as a rotational accelerometer with a reasonably low frequency proof mass. The horizontal and rotational ground accelerations could be obtained from the common and differential feedback signals, respectively. Their spectra are shown in Figure 5. We compared the horizontal ground acceleration observed with prototype-1 to that measured with a commercial reference seismometer (RION LA-50). They agreed well in the frequency band from 200 mHz to 1 Hz. The feedback signal was processed as a linear signal. This means that even with the nonlinear actuators, we can apply the standard method for linear signal analysis to obtain ground acceleration as long as the mass is held at the locking point. The ground rotation was also derived from the feedback signal plotted in Figure 4. Because there was no rotational sensor signal available for comparison, we could not confirm that the result (the solid line in Fig. 5b) corresponds to the true ground rotation, but it gives an upper limit of the ground rotation of the laboratory. These measurements were taken at the seismically quiet site of the SPring-8 synchrotron located on solid bedrock, which meets strict requirements for the large accelerator.

Prototype-2

We built the second magnetic levitation system (Fig. 6) as a rotational gravitational wave detector, which is very similar to a rotational seismometer (Ando *et al.*, 2007). The proof mass is hung below the superconductor, as shown in Figure 1, for better tilt stability. The mass has an inverted T-shape, and the main Nd magnet was attached to the top of the vertical stem to gain levitation force from the pinned magnetic field. In addition to the main magnet, there are two tiny pin-shaped Nd magnets attached to the ends of the horizontal stem to be used in coil-magnet actuators. Two solenoids were located at the extremities of the T-arms with the pin magnets inserted halfway into them. Torque for yaw control was applied by changing the current in the solenoids differentially. The measurements presented were performed with coil-magnet actuators[1]. A mirror was mounted at the cross point of the vertical stem and horizontal arms of the floating mass body, which acts as a reflector for an optical lever to monitor the yaw motion.

Prototype-2 was designed as a rotational sensor. To maintain its yaw rotation as free as possible, no supporting wire or other mechanical connection was established between the levitated mass and the ground. The superconductor disk in this setup was cooled by a pulse-tube (PT) cryocooler with no mechanical piston for quieter operation. The spectra of the vibrations generated by the cryocoolers used in our setups are shown in Figure 7. The disturbances induced by the PT cooler (solid line) are larger than the ambient noise

[1]Later we also implemented electrostatic actuators, and they successfully controlled the proof mass angular motion as with prototype-1.

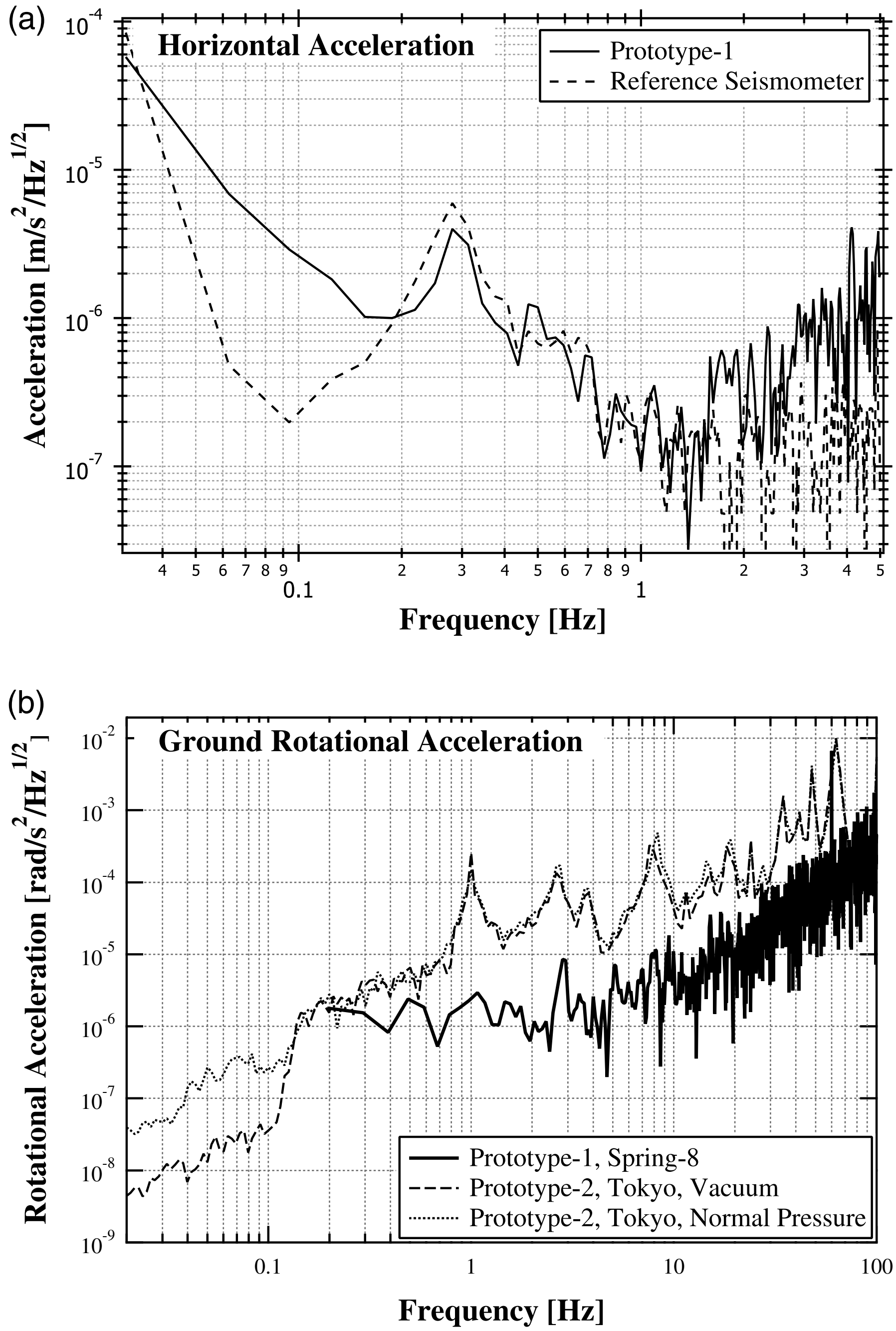

Figure 5. (a) Spectrum of horizontal ground acceleration observed with our prototype-1 accelerometer compared with that of a commercial seismometer. They agree well in the frequency band between 200 mHz and 1 Hz, in which the microseismic peak is clearly visible. (b) Spectra of rotational accelerations of the ground observed with prototype-1 and prototype-2. Although these results are still preliminary, they indicate the potential capability of the tested instruments.

only at the pulse frequency (∼3.8 Hz) and its harmonics; the G–M cryocooler (broken line) injects 10–100 times larger noise at the peak frequencies (1 Hz and its harmonics) compared to the PT cryocooler. Note that the floor of the G–M cooler spectrum is determined by the noise of the accelerometer used for the measurement and does not correspond to the actual cooler vibration noise. The superconductor is connected to the PT cooler through a vibration isolation heat link made of a bundle of very thin copper wires to further mitigate the vibration noise.

To study the mechanical responses of the proof mass, a transfer function of the yaw servo system was measured. By this measurement, it was proven that the natural period of the main yaw mode was longer than 10 sec, and there was no parasitic disturbance associated with the internal resonances of the system up to at least 100 Hz. This is not triv-

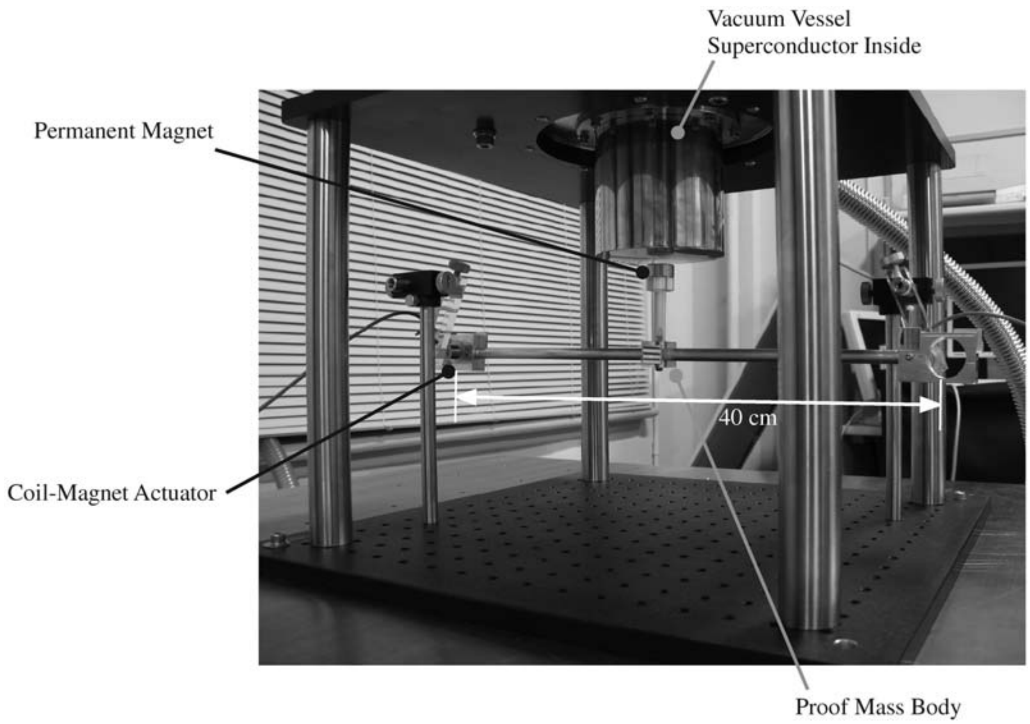

Figure 6. Photo of the prototype-2 magnetic levitation system specifically designed as a rotational motion sensor.

ial to realize with other traditional mechanical pendulums, and the result confirms that the magnetically suspended proof mass is promising as a reference mass for a rotational seismometer.

The ground rotation of the test site was obtained from the error signal of the servo loop shown in Figure 5b. The measurements were taken in a laboratory at the University of Tokyo, which is located in an urban area, and the ambient

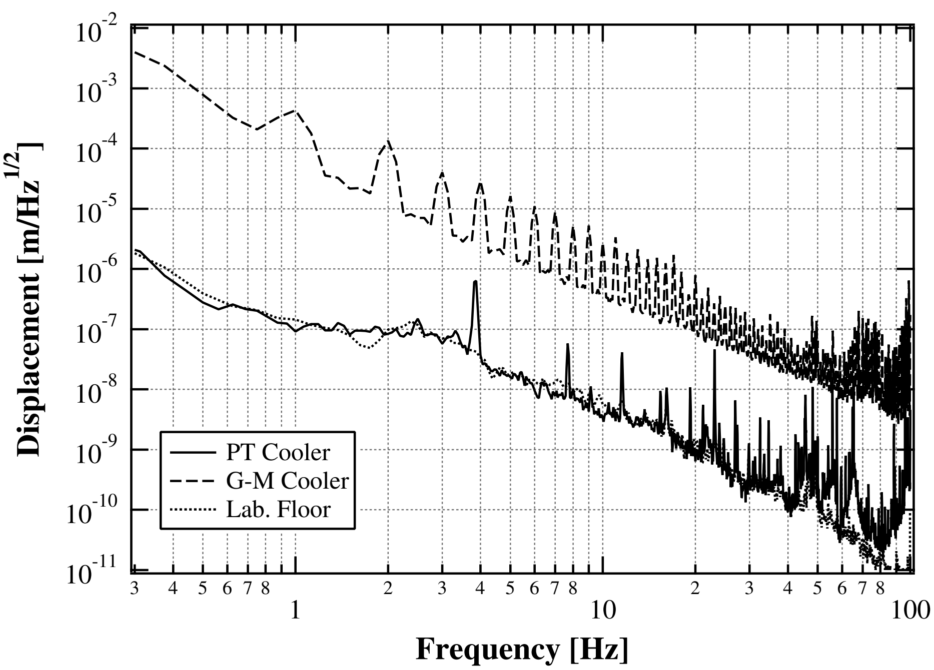

Figure 7. Spectra of vertical motions measured on the vacuum vessels used for housing the superconductor. The spectrum measured on the laboratory floor is shown as a reference (dotted line). Two types of cryocoolers were used to cool the superconductor. The PT cryocooler (solid line) was substantially quieter than the G–M cooler (broken line). Note that the floor of the G–M cooler spectrum was determined by the self noise of the accelerometer used for the measurement.

noise was expected to be relatively high. The measurements were taken with the proof mass at normal air pressure (dotted line) and in vacuum (20 Pa, dashed line). The results indicate that the disturbance from air flow was a major noise source for the instrument below 100 mHz; therefore, the proof mass should be kept in a vacuum. Except for the resonance at 980 mHz (proof mass tilt mode), most of the higher frequency peaks are identified as resonances of external structures, such as the optical bench or laboratory floor, and do not come from the seismometer itself. Similarly to prototype-1, the result may not fully reflect the actual ground rotation, but it indicates the upper limit or the resolution of seismometer prototype-2, which is already better than that of the high-end commercial sensors such as fiber optic or mechanical gyroscopes and fluid inertial transducers. Their resolution typically falls in the order of $10^{-6}\ \mathrm{rad/sec^2}/\sqrt{\mathrm{Hz}}$ at 100 mHz.

Conclusions

We began R&D of a new rotational seismometer that fills the performance gap between commercial transducers and leading-edge laser gyroscopes, with the aim of realizing broad observation networks of ground rotation. There are two key technologies included in the new design: magnetic suspension by means of the flux pinning effect of superconductors and a fully noncontact electrostatic actuator that allows virtually free rotation of a proof mass. Using two prototype systems, we successfully demonstrated the advantages and capabilities of the key technical components.

We will build another prototype that consists of a silent PT cryocooler and a proof mass body made of a monolithic disk (for better axial symmetry) and includes some other improvements based on the knowledge obtained from these tests. We also plan an observation with the third prototype placed in a vault for a period of several months in order to detect ambient ground rotation and provide a long-term evaluation of the instrument.

The experience gained through this R&D will also be useful for other applications such as spacecraft accelerometers and rotational gravitational wave detectors.

Data and Resources

All data used in this article were collected using the authors' prototype instruments described in the manuscript.

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