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ORIGINAL ARTICLE

Designs and test results for three new rotational sensors

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Abstract We discuss the designs and testing of three rotational seismometer prototypes developed at the Institute of Geophysics, Academy of Sciences (Prague, Czech Republic). Two of these designs consist of a liquid-filled toroidal tube with the liquid as the proof mass and providing damping; we tested the piezoelectric and pressure transduction versions of this torus. The third design is a wheel-shaped solid metal inertial sensor with capacitive sensing and magnetic damping. Our results from testing in Prague and at the Albuquerque Seismological Laboratory of the US Geological Survey of transfer function and cross-axis sensitivities are good enough to justify the refinement and subsequent testing of advanced prototypes. These refinements and new testing are well along.

Keywords Rotational seismology · Seismometry · Instruments · Instrument testing · Instrument design

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1 Introduction

We discuss tests, and briefly the designs, of three rotational seismometer models (early prototypes) developed at the Institute of Geophysics, Academy of Sciences (Prague). Two of these designs consist of a liquid-filled toroidal tube with the liquid as the proof mass; the torus moves relative to the fluid in response to rotational input motions. In contrast, the fluid is effectively fixed to the torus in translation and therefore is quite insensitive to such motions. Motions between the fluid and torus are detected by a suitable transducer; we tried both differential pressure and piezoelectric motion sensing and describe these here ("RP" and "RF" in Table 1). Finally, we created and evaluated a wheel-shaped solid metal inertial sensor with capacitive sensing and magnetic damping ("RC" in Table 1).

We performed a series of preliminary laboratory tests on the fluid torus devices at the Institute of Geophysics in Prague, including testing various geometries for the annular tube, examining the physical properties of the inertial liquid to be used (settling on chemically inert silicon oils, which are available across a wide range of viscosities), and comparing various mechanical-to-electrical transducers. These Prague tests were performed by means of a mechanical shake table generating rotational displacements of sinusoidal form in the frequency range 0.2–80 Hz. The angle of displacement was varied across the range 300 μrad to 100 mrad, and the actual velocity of the

Table 1 Names, descriptions, and tests performed on the sensors

Name	Sensor	Tests done[a]					
		1	2	3	4	5	6
RP	Rotation via pressure sense	✓	✓	✓	✓	✓	No
RF	Rotation via piezoelectric foil	✓†	No	No	◊†	◊†	No
RC	Rotation via capacitive sense	✓	✓	✓	✓	◊	No

✓ tests described in paper, *†* tests performed in Prague only, ◊ tests performed at either laboratory but not described in paper, *No* tests not yet performed

[a] Tests performed: 1—amplitude response vs frequency; 2—amplitude response vs amplitude (linearity); 3—phase response vs frequency; 4—cross-axis sensitivity, rotation-to rotation; 5—cross-axis sensitivity, translation-to-rotation; 6—sensor self-noise

shake table was recorded by a laser Doppler velocity sensor (Polytec series 3000; resolution 50 nm/s at a radius of 133 mm on the shake table, yielding angular resolution of 0.4 μrad/s).

Subsequently, we performed additional tests of these very early prototype designs (RP and RC models; RF malfunctioned) at the Albuquerque Seismological Laboratory (ASL) of the US Geological Survey with the help of their precision translational and rotational shake tables. In particular, we evaluated amplitude and phase responses and did various cross-axis tests. These early prototypes performed well enough to imply that they should be pursued to at least the point of fully engineered prototypes and that they should be tested in greater detail at ASL later (tests performed late summer of 2011, the subject of a follow-up paper). The candidates for additional development and testing certainly include the sensors we call "RP" (rotation by pressure sensor) and "RC" (rotation by capacitive sensing; Table 1). The "RF" (rotation by piezoelectric film) model was tested only in the Prague laboratory due to fluid transducer incompatibility in our ASL effort with that model; in Prague, RF displayed enough viable results to support its further development as well. Finally, we also looked at a capacitive displacement sensor with a vane inside the fluid torus, but this design did not work well enough to be evaluated in this paper.

As shown at the second International Workshop on Rotational Seismology (IWGoRS) in Prague, 10–12 October 2010, the Czech Republic has two other academic institutions in addition to our own where new models of rotational sensors have been developed. In the Institute of Geonics, Academy of Sciences (Ostrava), a new rotational sensor has been developed by modifying a standard Russian translational seismometer, the model S5S, into a balanced torsion bar configuration (Knejzlík at al. 2010). In the Prague Institute of Rock Structure and Mechanics, Academy of Sciences, a rotational sensor called the *Rotaphone* was developed from a set of standard mass-produced geophones specially arranged, inter-connected, and balanced (Brokešová et al., 2012; Brokešová and Málek 2010). A second device constructed by that institute is based on a rotational (gyroscopic) condenser (Štrunc 2010). These sensors have been tested in both laboratory and field conditions and the results are discussed in detail in the corresponding papers in this issue.

Rotational seismology and engineering, as new fields of endeavor, are discussed in detail by Teisseyre et al. (2006) and Lee et al. (2009a), inclusive of the papers in those compendia.

2 Devices tested

The devices tested are described briefly here and in Table 1:

1. Pressure transducer in fluid torus ("RP"): This design initially used a Sensor Teknik™ pressure sensor detecting pressure differentials across a fixed barrier caused by the momentum of a working fluid, a low-viscosity oil (in Prague a chemically inert silicon oil; at ASL "penetrating oil" that turned out to be chemically reactive with the piezoelectric transducer). Based on earlier results, this model was modified to use an All Sensors™ BLV**R**-L01D with a working fluid of isopropyl

alcohol. The tests reported later are for the latter pressure sensor. The more sensitive All Sensors™ BLV**X**-L01D with low-viscosity silicon oil or distilled water are likely candidates for future development of this sensor for which general performance is hopeful. Careful mass balancing within the fluid torus and possibly a helical fluid path to amplify pressure variations are other likely improvements. This design is discussed further by Jedlička et al. (2009).

2. Piezoelectric film in fluid torus ("RF"): In this model, silicone oil with a viscosity of 2 mPa s and specific mass 0.87 g/cm^3 was used initially (in Prague) with a transducer of a piezoelectric film sensitive to bending deformation and generating an electrical charge. Preliminary laboratory testing of this sensor was made in Prague, but at ASL we tried to test this piezoelectric film sensor with penetrating oil and isopropyl alcohol in place of the silicon oil; unfortunately, the oil and the alcohol proved to be chemically aggressive and in short order destroyed the piezoelectric film. This general class of sensor is discussed further by Čechák (2008).
3. The aluminum inertial wheel ("RC" for "rotation by capacitive sensing"): Uses cross-flexure mounts, magnetic damping, and a conventional differential capacitor pickup. Possible shipping damage to the cross-flexures and likely underdamping cause some anomalous behavior; nevertheless, its general performance could be evaluated and is promising. Improvements to the cross-flexures (or for unloading them during transit), increased damping, and improved pickups are likely improvements in subsequent versions. This was the quietest of the sensors in cursory noise tests (not presented here). The design is shown in Fig. 2. (Capacitive sensing is widely used and understood in seismometry.)

Models RP and RF are shown schematically and photographically in Fig. 1. Model RC is shown in Fig. 2.

Because piezoelectric films have low to zero response below 1 Hz, the RF variant probably is viable principally for exploration geophysics and microearthquake monitoring where response only above several hertz is sufficient.

In general, the sensors tested were designed principally for recording in the earthquake near-field, where the seismic waves may cause macroseismic rotational effects that can cause danger to life and property. For this purpose, rotation sensors sensitivity of 10^{-5} to 10^{-6} rad/s is sufficient.

[Our fluid sensors differ from the R-1, R-2, ARS-14, and related sensors. Notwithstanding that they also use a fluid-filled torus, they also use magnetohydrodynamic or electro-chemical principles; our RP and RF designs use other sensing methods and inert fluids with no RoHS concerns. In particular, we use a pressure-sensitive element in water or silicone oil. The physical principles of our liquid sensors are given in more detail by Jedlicka et al. (2009).]

3 The tests

We tested the devices shown in Table 1 for amplitude and phase response characteristics at 17–35 mrad/s peak input motions (peak observed rotations observed at three to a few tens of kilometers distance from earthquakes with magnitudes up to about five in Japan and Taiwan exhibit rotation rates up to ~0.6 mrad/s; Lee et al. 2009b). We also looked at their sensitivity as a function of input amplitude at a few frequencies (over the range of below 1–300 mrad/s). Because these devices tested are very early prototypes and not optimized in any way for noise, we did only cursory tests of their self-noise. Noise and linearity tests are not reported here. We did explore some noise characteristics of differing pressure transducers to identify a good candidate for that element of fluid-torus sensor RP.

3.1 Tests of amplitude and phase response

At ASL, amplitude response was estimated at a series of frequencies by driving the devices with rotational sine waves at amplitudes tightly controlled by the rotational shake table (Aerotech™ model ARMS-260-ES16780) and measured by a reference sensor, a fiber optic gyro ("FOG"; Litef™ model μFORS-1 part 143962-1000) while recording the sensor's response. Outputs of the units under test (UUTs) were kept in volts while those of the FOG were translated into rad/s, yielding velocity amplitude response in V/(rad/s) or in some cases converted to rad/s^2, yielding acceleration amplitude response in V/(rad/s^2). No transfer function deconvolution was attempted in any test. In

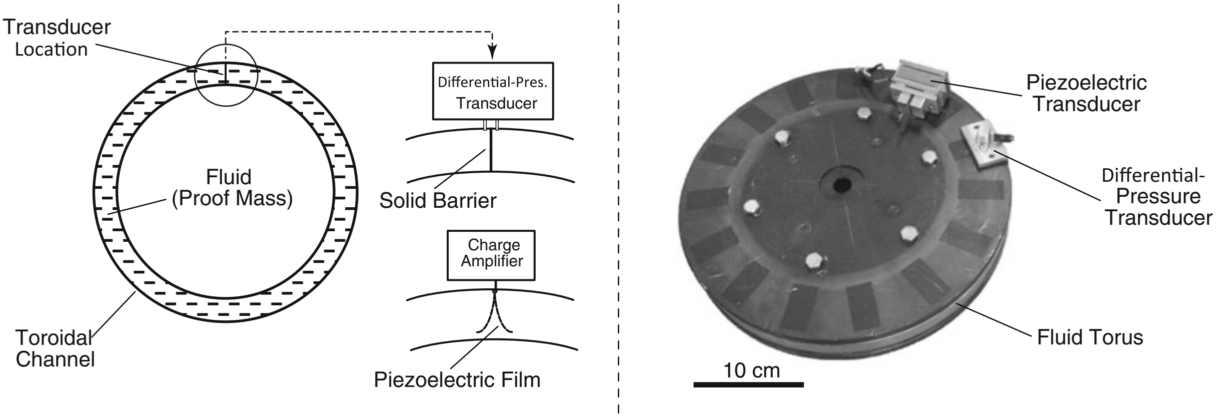


Fig. 1 The toroidal liquid sensors RP and RF. Schematic diagram at *left* and photo at *right*. The torus is a slot cut into an aluminum plate

any case, correction for a transfer function is unnecessary for the FOGs since they are highly linear and flat. The FOGs are a bit noisy (rms is of the same order as the Earth rotation signal, 12 μrad/s, which these FOGs do see as a modest offset at zero shake-table input). Additional sensor information can be found at http://www.northropgrumman.litef.com/fileadmin/downloads/Datenblatt_uFors-36_-1.pdf.

Timing issues with the FOG reference data limited phase measurements to values normalized to zero phase at 2 Hz (because we had to synchronize the UUT and FOG time series with a brief, 2-Hz timing pip at the start of the sequence of test sine waves). Thus, sensor outputs at this frequency have a relative phase of ~0° at 2 Hz. This timing uncertainty may make phase measurement unreliable at high frequencies (though no such problem is obvious in our results) and in cross-axis tests (where the timing pip could not be read, so no phase estimates were made). These FOG timing issues have now been resolved, so the tests performed in the summer of 2011 will yield absolute phase when analyzed.

The RP model is expected to respond in proportion to rotational acceleration, whereas the reference FOGs respond in proportion to rotational velocity; we graphically corrected for this difference in Figs. 3 and 4. It is not clear why there are several decibel variations between the three test runs in Fig. 3, but that range of results is some measure of test accuracy and sensor stability; sensor instability would be no surprise in such early prototypes not yet optimized for noise and stability. In any case, our result implies good performance of the sensor in this test, so the concept clearly is worthy of additional development. This design also could be improved with force feedback, allowing one to shape the response to be flat to rotational velocity.

Model RF was tested only in Prague, as discussed earlier. Figure 5 shows its amplitude response. RF works well in the frequency range 4–80 Hz. For frequencies lower than 10 Hz, the sensor works as a rotational accelerometer, while for frequencies above this its output is proportional to angular displacement. A local maximum is present at about 11 Hz, presumably due to resonance of the piezoelectric film moving

Fig. 2 The inertial wheel capacitive transducer sensor “RC”. Schematic diagram at *left* and photo at *right*. Pivot is a cross-flexure

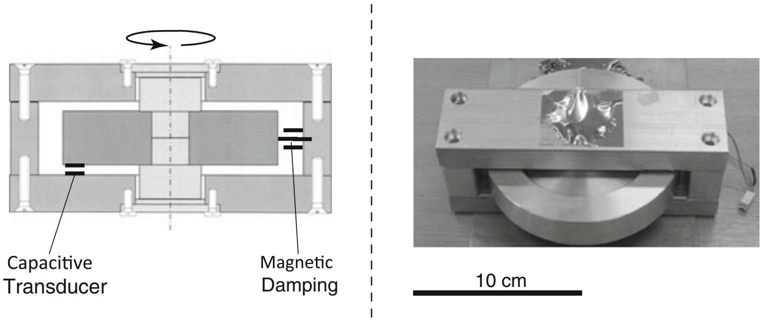
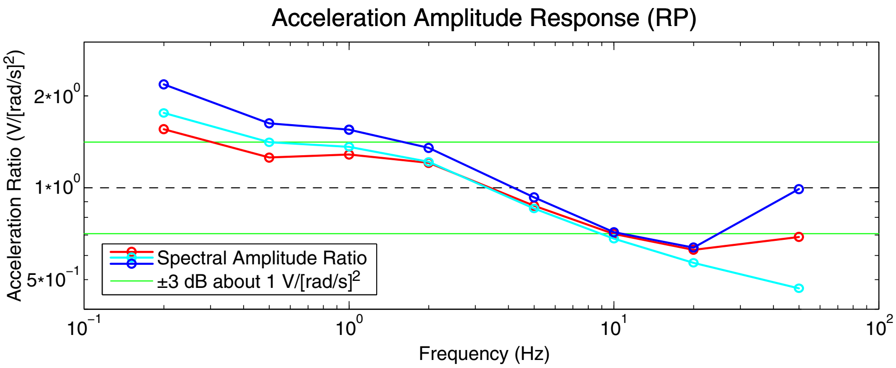


Fig. 3 Amplitude response of RP, measured three times. The *green lines* denote ±3 dB tolerance, but the other three imply a viable result of the type anticipated for this rotational acceleration sensor. Three plotted *color lines* (*dark blue*, *light blue*, and *red*) represent three identical tests and illustrate the present limits of test accuracy



within the fluid; we expect to reduce this local maximum by using a liquid with somewhat higher viscosity, thereby increasing damping.

Testing of model RC confirmed that it is responding reasonably well (Fig. 6), though it appears to be underdamped in this prototype (the resonance peak probably is undersampled in frequency and not fully resolved). The instrument also shows evidence of damage to the cross-flexure pivots during transit from Prague to Albuquerque (it seemed to stick or "oil can" at small input amplitudes). It appears to have response proportional to acceleration below ~1 Hz but proportional to displacement above that frequency. This result implies additional poles over what is seen in a geophone and suggests that a force-feedback variant might be called for. Nevertheless, its response is quite hopeful and it is worthy of additional development.

3.2 Test of cross-axis sensitivities

Cross-axis sensitivities between rotation and rotation (off-axis rotational inputs) or between translation and rotation (translational inputs in several directions) were tested on rotational and translational shake tables

Fig. 4 Phase response of RP (three tests). The large phase angles at frequency extremes are not yet understood but are outwardly reasonable and not unusual among open-loop sensors. In addition, phase at long periods may be unreliable due to weak UUT output, while those at high frequencies may be contaminated by timing errors between UUT and the reference FOG, though no obvious effects of timing errors are seen here

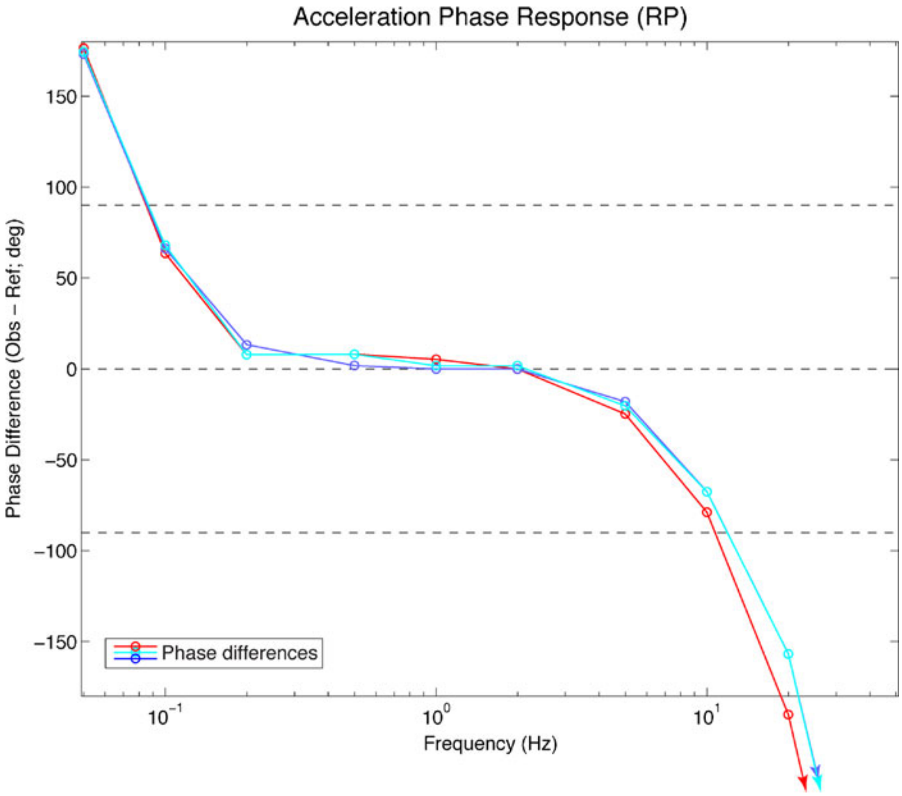
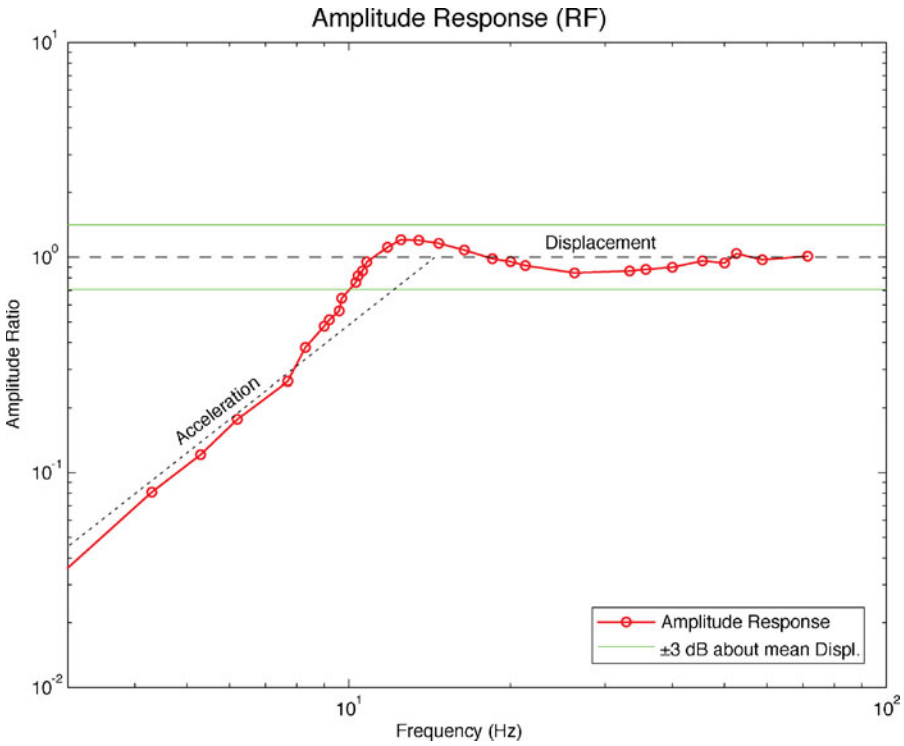


Fig. 5 Frequency–amplitude characteristics of the RF sensor plotted by means of a recorder with input impedance 20 kΩ. In the range 0.4–1 Hz, the sensor works as an accelerometer, while from 1 to 70 Hz it responds in proportion to rotational displacements. Tested in Prague, October 2010



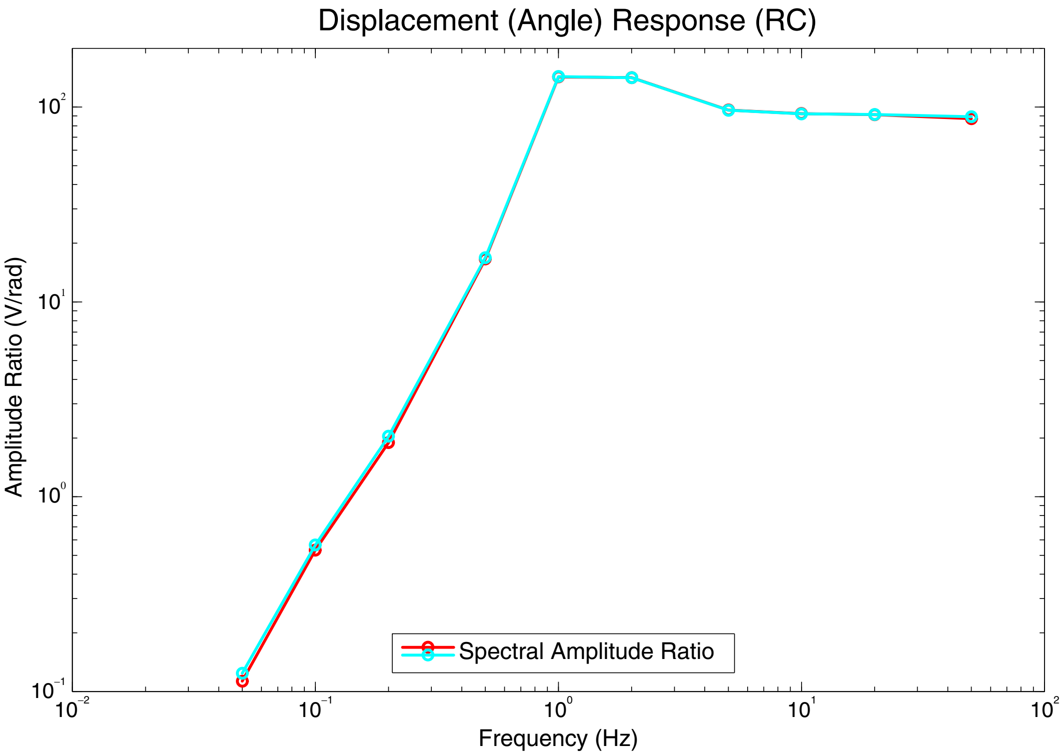


Fig. 6 Amplitude response of the RC sensor. Except for a modest resonance peak (which may not be fully mapped at this test frequency spacing), this sensor has a flat transfer function in the range 0.7–27 Hz

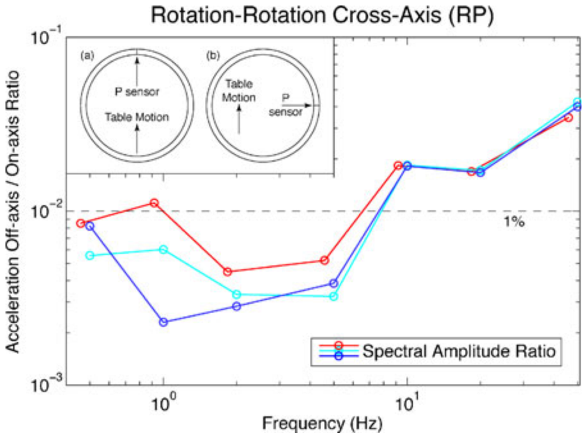
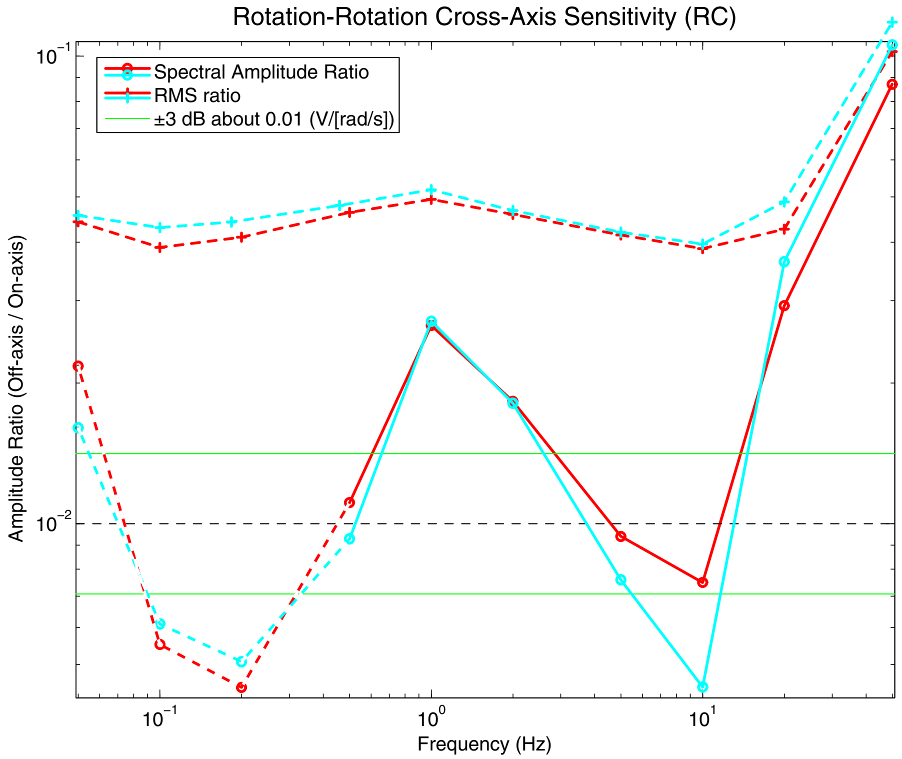


Fig. 7 Rotation-to-rotation cross-axis sensitivity of RP (*insets a* and *b*). The response is roughly linear with frequency as is appropriate to an acceleration sensor (cf., Fig. 1). It is about two decades below that response (Fig. 3) except at high frequencies

in a manner similar to measuring a response function. Translation-to-rotation cross-axis is of particular concern since translational motions from earthquakes are stronger than rotational motions and because precise proof-mass balancing is required to minimize this problem. Indeed some balance issues arose but appear resolvable through small design changes and manufacturing care. The small amplitudes of UUT signals obviated calculation of phase (we could not synchronize to the very weak 2-Hz time marks), but amplitudes are the essence of cross-axis tests and were recoverable in general.

For RP (Fig. 7), we show reasonable rotation-to-rotation cross-axis response, generally below the industry norm of 1 % though there are issues at high frequencies that we probably can address during redesign (presumably resonance phenomena). We also have results at 5 Hz for translation–rotation cross-axis, where we found 0.3–0.4 V/(m/s) when the translational motions are either perpendicular to the plane of the torus or in that plane, but with the pressure sensor oriented in the direction of motion (that is, with fluid mass equally distributed on either side of the sensor; Fig. 7, inset a). This value rises significantly to about 6 V/(m/s) when translational motion is in the plane of the torus, but the pressure sensor is at right angles to that motion (Fig. 7, inset b). We infer from this contrast that balancing the mass of fluid on opposite sides of the torus (about the axis of motion) is

Fig. 8 Rotation-to-rotation cross-axis sensitivity of RC, *dashed* where unreliable. Much of the spectrum is near or below the 1 % industry standard, but there are issues near the sensor's natural frequency and at high frequencies. Tested at ASL in November 2010



essential for keeping this cross-axis term small. That is, we infer that even the small volume of fluid displaced by the fixed barrier and the pressure sensor itself causes significant sensitivity to translational motions by placing a larger fluid mass on the opposing sides of the torus. Careful engineering and manufacture of the fluid channel should eliminate this problem by balancing the fluid mass about all possible axes of translational motion.

We note that the rotation angle inferred from translational inputs (when translated into an an equivalent acceleration error signal via integration to tilt angle θ and conversion to gravity-induced acceleration signals by $g\sin\theta$) must be under 1 PPT of the true translational acceleration input to the sensor. This is so because true rotations are on the order of a few percent (perhaps less) of translation when so translated, and the translation-to-rotation error signals need to be at least another order of magnitude smaller than that lest they exacerbate translational errors rather than alleviating them when solving inertial navigation equations for true translational displacement in the horizontal plane (e.g., Lin et al. 2010).

RC has a more complex pattern of rotation–rotation cross-axis sensitivity (Fig. 8). That sensitivity is at or below the 1 % industry standard at many frequencies but above that norm at the sensor's natural frequency and again at high frequencies. Mechanical imperfections, including the suspected pivot damage to this unit, may be responsible for both deviations. Thus, we suspect this concern to be alleviated in follow-on units with stronger (or better protected) pivots and damping closer to 0.7 (Fig. 8).

Our measurements and the experience of others lead us to agree that non-zero translational sensitivity of fluid rotational sensors to translational inputs remains a critical problem that must be solved. If ring fluid sensors are optimally balanced (equal proof mass on all opposing sides), then the sensitivity to translations should be very small, within the requisite 0.1 % maximum cross-axis. We have plans in this matter and in recently tested newer variants of ring fluid sensors that lowered this cross-axis sensitivity. As of this writing, these tests have not been fully analyzed, mostly due to the focus of the authors on the present special issue of the *Journal of Seismology.* These data will be analyzed and reported in a subsequent paper.

4 Summary and plans

In this first stage of the Czech–American project on new types of rotational sensors, a series of seismometers sensitive to rotational inputs, and largely insensitive to translational seismic inputs, were constructed in the Institute of Geophysics, Prague, and tested preliminarily there. Several advanced models were then carried to ASL in New Mexico and the surviving three of these were tested there comprehensively in November 2010. Those designs and tests are described in this paper.

Three of the models tested (RP, RF, and RC in Table 1) were found to be viable with good prospects for improvement. The tests performed on these sensors demonstrated their utility for recording rotational strong ground motions and suggested future technical alterations to improve their sensitivity, reproducibility, immunity to translation, and efficacy. These attributes are being exploited in present efforts in Prague to refine and improve the three designs and produce improved prototypes for further study. These new prototypes were tested in depth at ASL in the summer of 2011, and the new designs and test results will be published in a subsequent paper.

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