Tilt sensor and servo control system for gravitational wave detection.

Y. Cheng[†], J. Winterflood, L. Ju, D.G. Blair

Department of Physics, University of Western Australia, Perth 6009, Australia.
†Currently: Department of Physics, China University of Geosciences, Wuhan, 430074, P.R. China.

Abstract

This paper describes the design of a novel double-flexure 2-axis tilt sensor with a tilt readout based on an optical walk-off sensor. The performance of the device has been investigated theoretically and experimentally. The walk-off sensor has demonstrated a sensitivity of 10^{-11} rad/√Hz at 1Hz. The tilt sensor has measured seismic noise ~10^{-9} - 10^{-10} rad/√Hz for frequency in the 2~10Hz range.

1 Introduction

Gravitational wave detection requires high performance vibration isolation. To achieve low residual motion at low frequency, it is necessary to use a 3-D ultra-low frequency pre-isolator stage (f<0.05Hz) before the use of conventional vibration isolators (f ~ few Hz). Such a stage can reduce the seismic drive to the normal mode resonances of the isolator stage and thus reduce the residual motion by two orders of magnitude compared with a conventional multistage isolator [1]. High performance vibration isolation systems are being intensively developed at many sites for the VIRGO, TAMA, LIGO, and AIGO gravitational wave detection projects [2,3,4], and many new vibration isolator structures have been invented to allow ultra-low frequency performance. These include the inverse pendulum [5], the Scott-Russel linkage [6], the torsion crank suspension [7], and the folded pendulum [8]. It has been shown that in the absence of tilt noise, 3-D pre-isolators allow the reduction of RMS residual motion of an isolation system down to nanometres for frequencies above 0.2Hz [9].

Generally the effect of seismic tilt is far smaller than seismic translation and can be neglected for a suspension system without horizontal pre-isolation. With reasonable pre-isolation applied, the translational coupling can be reduced to the point where tilt coupling becomes noticeable and dominant. Seismic tilts perturb the vertical alignment of a pre-isolation structure giving rise to a horizontal acceleration equal to the tilt angle times *g*, regardless of the effective length(s) of any pre-isolator pendulum(s). Doubly integrating this acceleration gives residual motion noise. Once pre-isolation has reduced the translational coupling below this level, then no improvement is achieved by better horizontal isolation. To achieve ultimate performance, it is therefore essential that seismic tilts be accurately measured and suppressed. In this paper we describe design and construction details of a novel tilt sensor based on the optical *walk-off sensor* [10].

2 Mechanical design of the tilt sensor

The concept of the tilt sensor is very simple. It consists of a high moment of inertia disk suspended near to its center of mass to create a low frequency rocking mode. Above resonance it acts as an inertial rotational reference. To decouple it from translational motion and give it DC sensitivity to tilt (and acceleration), the entire device is suspended on a pendulum link. The tilt sensor, as shown in figure 1, consists of a high moment of inertia reference mass and the optical walk-off readout system described below. The reference mass is a 50kg disk suspended by a rigid arm containing 2-D flexures at each end. For high moment of inertia the disk is structured as a wheel with a thick rim. The suspension point is just below the center of mass creating as slight inverse pendulum to null out the flexure spring-rate and achieve a very low rocking frequency. There are four adjustment masses on the top of the test mass to allow fine adjustment of the center of mass and to tune the resonant frequency. The rocking frequency of the disk for near center of mass suspension is 100mHz. This has been tuned down to 58mHz by lowering the suspension point below the center of mass by about 0.4mm. At this frequency the Q-factor is about 10.

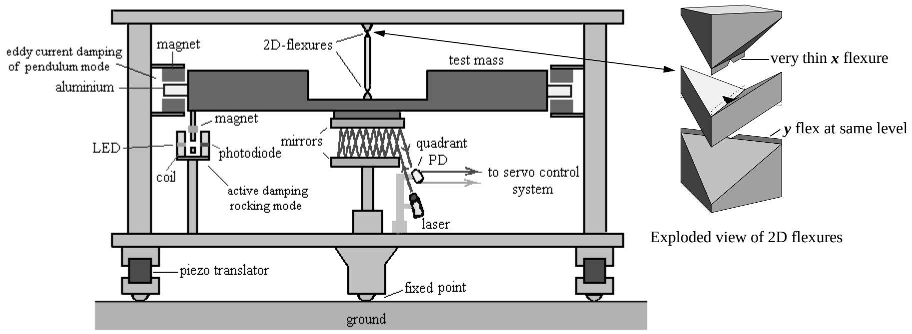

Fig. 1 Layout of the walk-off tilt sensor. One of the mirrors is mounted beneath the test mass. The other, laser, and quadrant photodiode are fixed on the base plate of frame.

The 2-D flexures simplified and exploded in figure 1, are made from monolithic blocks of low-loss high-strength material (maraging steel) using precision electric discharge machining. The flexing membranes have a length of 0.4mm, width of 13.5mm and thickness of 80µm. To achieve high sensitivity it is necessary to suppress the pendulum mode and the rocking mode. The pendulum mode can be suppressed by simple eddy current damping using a horizontal conductive sheet in a vertical solenoidal field created by NdFeB magnets as shown in figure 1. The frequency of the pendulum mode was 1.85Hz. Damping of the rocking mode must be done with more care to prevent noise injection. This was achieved using active damping with a sensitive shadow sensor and magnet/coil pair for force actuation. The rocking motion of the test mass was critically damped, mainly to enable the walk-off sensor to remain within its dynamic range.

3 Optical readout system - walk-off tilt sensor

The readout of the tilt sensor is a high sensitivity optical walk-off angular displacement sensor [10]. The optical walk-off sensor consists of a pair of nearly parallel high reflectivity mirrors. A laser beam injected at the appropriate angle will be reflected back and forth between the mirrors, following a parabolic trajectory across the mirrors, re-emerging with a displacement in both horizontal dimensions which is very sensitive to the angles between the mirrors. A quadrant photodiode senses the change in position of the laser spot and thus provides a 2-D tilt signal. The spot displacement on the quadrant photodiode increases as the number of bounces squared [10]. For best sensitivity we used a concave mirror (with a radius of curvature of 4m) to replace the upper flat mirror, enabling the laser beam to re-focus at the photo-detector. The beam can actually re-focus many times in its trip across the mirrors depending on the separation between mirrors and number of bounces. The final sensitivity of the walk-off sensor is inversely proportional to its dynamic range. In our case we used 20~30 beam bounces with a final beam spot size about 1.0~1.4mm to achieve an optimum balance of sensitivity and dynamic range. The physical set up consisted of two high reflectivity (>99%), 2” diameter mirrors and a 4mW He-Ne laser. We ground two small flat sections on the diameter of the lower flat mirror to allow the beam to enter and exit as close to the coated edge as possible. (Standard mirrors have an un-uncoated margin around the edge making it difficult to insert the beam at a steep angle close to the edge).

4 Ground tilt noise and the instrument noise floor

It is very difficult to confirm the noise level of a very sensitive tilt sensor. The best estimate is obtained by clamping the pendulum, but this also eliminates internally generated noise such as thermal noise or creep noise in the flexure. The noise floor of the tilt sensor appears to be dominated by laser noise. We investigated the readout noise by clamping the mirrors. It was measured to be ~10^{-11} rad/√Hz above 1Hz, as shown in figure 2.

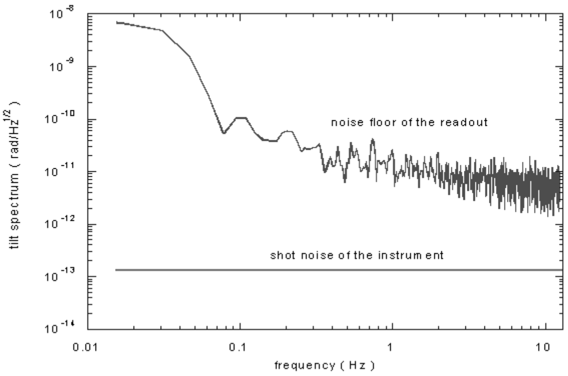

Fig. 2 The noise floor of the tilt sensor. It is 10^{-11} rad/√Hz at 1Hz.

This noise level is far above the shot noise of the readout which was measured to be ~1.32×10^{-13} rad/√Hz at 1Hz. We believe that beam jitter (pointing) noise of the He-Ne laser dominates the noise floor. However it is clear from ground tilt measurements that the noise level achieved is 1~2 orders of magnitude lower than the lowest levels of environmental tilt noise in our laboratory. We believe that if a lower noise laser source was used we could lower the instrument noise floor considerably.

Until recently, there has been little investigation of seismic tilts in the frequency range of 0.1~5Hz [11,12]. A rotational accelerometer was used at the VIRGO laboratory [13] to measure the seismic tilt acceleration spectrum above 1Hz. These results translate to an angular displacement seismic noise level of 3×10^{-7} rad/√Hz at 1Hz. Below 1Hz the signal to noise ratio was poor.

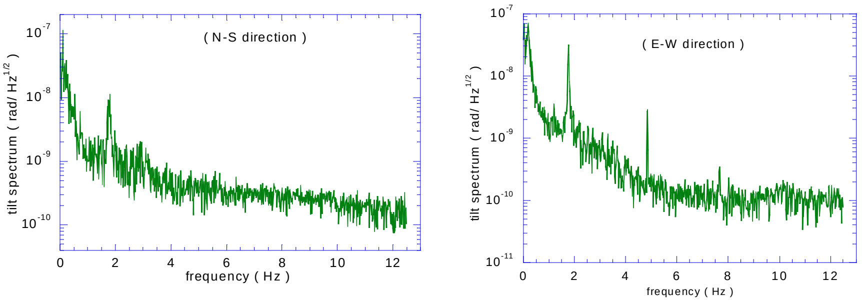

Fig. 3 The seismic tilt noise in our basement laboratory around midnight.

We directly measured the seismic tilt angle displacement spectrum in two orthogonal directions, as shown in figure 3. The seismic tilt noise in our basement laboratory at midnight is about 10^{-9} rad/√Hz at 1Hz. During daytime human activities nearby greatly affect the measurement and increase the seismic noise to 10^{-6}~10^{-7} rad/√Hz. Figure 4 shows the ground tilt effect when a person of 75Kg walks near the tilt sensor. This gives rise to ~10^{-6} radians of ground tilt.

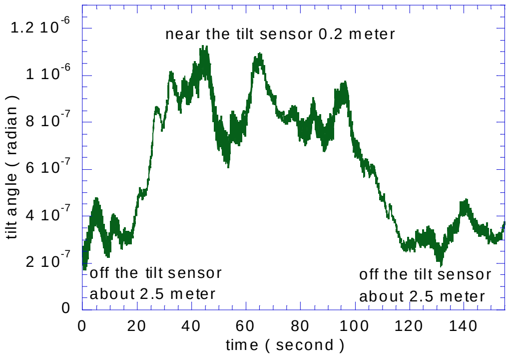

Fig. 4 Ground tilt due to human activities are typically 10^{-6}~10^{-7} radian. Data showing typical levels of human generated tilt noise and tilt effect of a person walking to within one meter of the tilt sensor. The sensor is mounted on a 660kg steel slab on the concrete foundation.

5 Transfer function of tilt sensor

If a tilt sensor is to be used to actively suppress tilt noise in a vibration isolator, it is necessary to investigate the transfer function of the tilt sensor, that is the ratio of the angle ψ read-out to the tilt angle ϕ applied, as a function of frequency. For this purpose we set up a system as shown in figure 5(a), placing piezo legs under the tilt sensor to apply tilt. Points A and B beneath the base plate of the frame were used to apply the tilt signal, as shown in figure 5(b). Point C is a fixed support point. The displacement capability for the loaded piezo translators (PZT) was 11~12 μm (PI components P-802.10). As the PZTs provide a unidirectional displacement, a mid-range offset voltage was applied to achieve an offset displacement of 5 μm, giving a total dynamic range for applying tilt of ~ ± 10^{-5} rad. A chirp signal was applied to the PZT legs to drive the lower platform and the resultant tilt was monitored with shadow sensors. The transfer function between this applied tilt and the value read-out from the walk-off sensor was measured with an FFT spectrum analyser (which also generates the chirp driving signal).

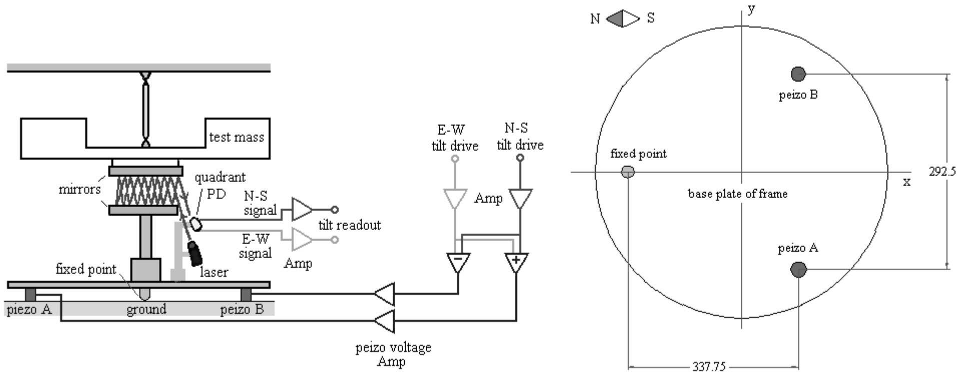

Fig. 5 (a) The schematic of servo control system to suppress the ground tilt. (b) The mounting location of the two peizo translators.

The measured response of the system to the excitation is shown in figure 6 together with the theoretical expectation. Mathematical analysis of the system shows two normal modes for each axis although in the transfer function the pole at the pendulum mode resonance is cancelled by a zero at the same frequency. In the measurement the cancellation is not quite perfect and so the pole zero pair at the pendulum mode frequency can be noticed at 1.85Hz. It can be seen that the transfer function agrees well with theory above 0.06Hz while below this it shows unexpected gain. We expect that the transfer function measurement at such low frequencies was affected significantly by various sources of noise such as temperature induced air motion

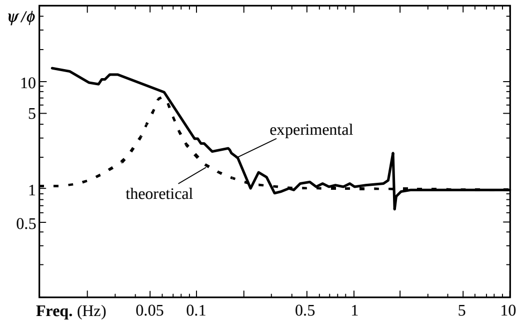

Fig. 6 The measurement of transfer function of tilt sensor and the comparison with theoretical calculation

For the purpose of vibration isolation the frequency range, 0.2~5 Hz, is most important for servo control since the seismic tilt and translation feeding through the isolation dominate in this frequency range[9]. If the 1.85Hz resonance proves to be a problem for servo control, the length of pendulum linkage could be shortened so that the pendulum mode frequency exceeds 5Hz.

6 Discussion and conclusion

A seismic tilt sensor in the 0.1~10Hz band using a high moment of inertia test mass appears to be a practical means of achieving high sensitivity. The walk-off sensor provides a method of achieving a simple high sensitivity, with an easily controllable balance between sensitivity and dynamic range. Noise performance appears to be limited by laser jitter. Improvement would be straight forward using a stabilised laser.

By applying tilt signals we were able to confirm reasonable agreement between the experimental and theoretical transfer functions at all frequencies except for an unexplained enhancement at low frequency. The transfer function measurements allowed an assessment of the difficulties in providing a system to achieve active tilt control. The tilt actuation system illustrated in figure5(b) was found to be unsuitable because its geometry leads to strong cross talk between rotation and translation. Any active control system should take this into account, by designing the centre of rotation actuation to be accurately coincident with the centre of rotation sensing.

In conclusion, we have demonstrated high sensitivity down to the lowest tilt noise levels in our basement laboratory of $\sim 10^{-9}$ rad/√Hz at 1Hz and 10^{-10} rad/√Hz at 10Hz. The walk-off sensor readout has been demonstrated at the level of 10^{-11} rad/√Hz. Results show that human activity generates noise levels orders of magnitude larger than the lowest observed levels. This is likely to cause significant difficulties in the control and isolation of test masses in advanced gravitational wave detectors which aim for high sensitivity at low frequency.

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