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Prototype of interferometric absolute motion sensor

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ABSTRACT

For many applications, there is an increasing demand for low cost, high resolution inertial sensors, which are capable of operating in harsh environments. Based on recent developments in optical seismometry, this paper presents a new small interferometric inertial sensor with a resolution of $3\,\text{pm}/\sqrt{\text{Hz}}$ above 4 Hz. Compared to most state-of-the-art devices, this prototype does not contain any coil, which offers several important advantages: (i) when it is used for active control, it magnifies the control performances around the sensor resonance; (ii) it decreases the thermal noise in the suspension (Brownian motion), (iii) it is compatible with magnetic environments (like particle collider); (iv) as the interference fringes sweep continuously across the detector, it allows a real time calibration of the parameters, and thus the calibration can be continuous monitored and updated.

1. Introduction

Inertial sensors have been used for more than a century mainly to answer the needs of seismology, the science which studies the propagation of waves through the Earth. Depending on the frequency range of interest, three types of sensors are commonly used to measure seismic vibrations [1]: seismic accelerometers, geophones and broadband seismometers. A comparison of these inertial sensors can be found in [2].

For more than 30 years, seismometers have reached sufficient resolution and dynamic range to capture seismic signals at most location of the Earth surface in a broad frequency range extending typically from 1 min to 100 Hz (see e.g. [3–6]). However, there is still a continuous demand for high-end instruments, more efficient and better adapted to some specific applications. In this respect, recent developments in optical technologies offer interesting perspectives for novel inertial sensors. In the oil/gas and mining industry for instance, inertial sensors capable of operating in harsh environments (e.g. down-holes, boreholes) are needed, and optical seismometers without electronics and insensitive to temperature and high pressure [7–10] have been developed. In the field of security, miniature autonomous optical inertial sensors have been tested for the detection of detonation arising from nuclear tests conducted by countries engaged in nuclear proliferation [11–13].

Besides seismology and the aforementioned applications, there is also a demand for inertial sensors for precision engineering and scientific experiments requiring a very stable environment [14]. Typical applications are: (i) Tests and validation of space equipments on vibration-free space simulator. (ii) Isolation of lithography machines in the semiconductor industry. (iii) Reduction of vibrations of atomic force microscopes (support and sample) for increasing their resolution. (iv) Stabilization and isolation of large instruments dedicated to extreme experimental physics, like gravitational wave interferometric detectors or future particle colliders. In these systems the immunity to environmental disturbances is obtained by actively cancelling the structural vibration measured by inertial sensors [15].

A few other prototypes of optical inertial sensors and seismometers have been developed and reported in the literature. They are based on Fabry-Perot interferometer [22], fiber interferometer [19–21], triangulation system [23], fiber Bragg grating [24,25], optical encoder [26] or grating sensor [27]. More recently, optical accelerometers have been proposed for measuring the mechanical vibration of gravitational wave detectors [16–18].

However, to the best of the authors' knowledge, there is no commercial seismometer capable of fulfilling the requirements for applications in advanced active vibration isolation systems, i.e. small, sub-nanometer resolution at low frequency, and compatible with a magnetic environment. In this paper, we present a non-magnetic Optical inertial SEnsor (NOSE), which is based on a horizontal pendulum and a Michelson interferometer. It is small,

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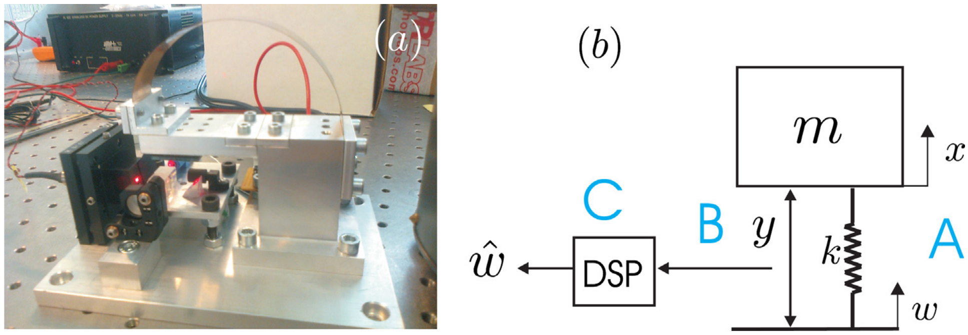

Fig. 1. Picture (a) and schematic (b) of the prototype of the interferometric inertial sensor NOSE. (A) Single degree of freedom oscillator, (B) interferometric displacement sensor and (C) acquisition processing unit.

passive, and measures seismic motion in the vertical direction.[1] We will show that, besides the compatibility with magnetic environment, the absence of coil offers also several advantages.

The paper is organized as follows: The new sensor is presented in Section 2. Section 3 contains experimental validations, and Section 4 draws the conclusions and directions for improvements.

2. Description of the optical inertial sensor

The sensor is composed of three main parts (see Fig. 1): A single degree of freedom (d.o.f) oscillator (A), an interferometric displacement sensor (B), and an acquisition processing unit (C). Each of the three parts are detailed in the following sections.

2.1. Mechanics

The mechanical part consists of a horizontal pendulum, connected to a rigid frame through a flexural joint, made of CuBe alloy. A leaf spring, made of the same alloy, is used to adjust the equilibrium position of the inertial mass and compensate for gravity. The oscillator is characterized by an inertial mass $m = 0.055$ kg, a principal resonance frequency $\omega_0 = 6 * 2\pi$ rad/s (tunable) and spurious resonances above 100 Hz.

Usually, and most specifically for geophones, a high damping of the inertial mass, i.e. a small Q factor, is imposed in order to increase the bandwidth of the sensor and reduce its sensitivity to miscalibration. A critical damping is obtained by connecting a resistor to the sensing coil. On the contrary, our inertial sensor is characterized by a high Q factor (around 60) because it does not contain any loaded coil. A *first* advantage of the coil-free configuration is that the sensor is compatible with magnetic environments like encountered in proximity to particle colliders. A *second* advantage is that the high Q decreases the thermal noise in the suspension (Brownian motion) defined as [28]:

$$B(f) = \frac{\sqrt{4k_B T\omega_0 m/Q}}{m(2\pi f)^2} \simeq 10^{-11} f^{-2} [m/\sqrt{Hz}] \quad (1)$$

where k_B is the Boltzmann constant, $T = 300\,K$ is the temperature and ω_0 is the angular resonance frequency.

When the inertial sensor is used for active vibration isolation, the high Q offers a *third* advantage because it magnifies the control performance around the sensor resonance. As an example, consider the single d.o.f. isolator shown in Fig. 2(a) where a sensitive equipment (m) mounted on an active suspension is represented. The motion x of the equipment is measured with an inertial sensor. Then, the signal is filtered by a filter $H(s)$, used to generate a feedback force f. Fig. 2(b) shows a typical transmissibility (x/w) of the suspension when the control is turned off (solid line), and turned on for two sensors: a geophone critically damped (dotted line) and NOSE (dashed line). The same controller $H(s)$ has been used for both sensors. The curves have been obtained with a numerical model of the isolator, and the following numerical values of the parameters: $m = 100$ kg, $k = 1.6$ MN/m, $c = 1200$ Ns/m. The figure shows that, for both sensors, the transmissibility has been reduced by the feedback operation in a large bandwidth, extending from a fraction of the geophone corner frequency to a multiple of the resonance of the equipment.

However, for NOSE, the strong mechanical amplification at the resonance improves significantly the isolation in a frequency range around this resonance, while using the same crossover frequencies for both sensors. Such feature can be particularly interesting to cancel narrow band excitations. Moreover, as the photo-diodes signals amplitude remains bounded (see Section 2.3), the peak of performance is not limited by the classical trade-off between resolution and dynamic range.

On the other hand, when the sensor is not used in a feedback loop, the low damping of the inertial mass becomes a disadvantage because it reduces the bandwidth and because large oscillations of the inertial mass are superimposed to the useful signal. Still, the absence of coil remains interesting for the compatibility with magnetic environments.

2.2. Interferometric sensor

In order to measure the relative displacement between the inertial mass and the support, we have developed a sensor based on a Michelson interferometer, adapted to enable the measurement of both quadratures of the signals as in [7,29]. The optical scheme is shown in Fig. 3.

The laser source is a He–Ne laser with a wavelength of 632.8 nm. The input beam, linearly polarized at 45°, is first split in two orthogonal beams by means of a 50/50 non polarizing beam splitter (BS). Each beam is then reflected on the mirrors M_1 or M_2. M_1 is fixed on the inertial mass and M_2 is mounted on a miniature two d.o.f. tilt stage to enable the alignment of the interferometer. Additionally, the arm d_2 contains a $\lambda/8$ waveplate to generate a circularly polarized beam (it is in an elliptical polarization after 1 pass, and a circular polarization after double-passing the wave plate). The two beams are recombined in the beams splitter (*BS*). The vertically and the horizontally polarized components of the recombined beam are then separated by a polarizing beam splitter (*PBS*). The intensity in the two beams are finally measured by means of two photodiodes. The laser source is mounted on a four d.o.f. stage (two translations and two rotations) to adjust the position and the angle of the beams

[1] In principle, the sensor is also capable to measure seismic motion in the horizontal direction. However, this feature has not been investigated.