INTERFEROMETRIC ACTIVE INERTIAL ISOLATION FOR EXTENDED STRUCTURES

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Abstract

This article presents an active vibration isolation strategy combining centralized interferometric inertial control and decentralized force control loops. This innovative approach is designed to comply with the stringent requirements of particle detectors where coils and magnets cannot be used. The technology and control approach developed is also of interest for potentially improving the performance of isolators used in gravitational wave detectors such as LIGO, whose active platforms performance is limited by inertial sensor noise at low frequencies, and control bandwidth at high frequencies.

1 INTRODUCTION

Effective isolation from ground vibration is required for many applications including lithography machines, atomic force microscopy, medical imaging, and large instruments dedicated to experimental physics [1]. Among them, the stabilization of the electromagnets of future compact linear particle collider (CLIC) is particularly challenging [2-4]. It is estimated that the RMS value above 4 Hz of the last electromagnet vertical displacement should not exceed 0.15 nm. Beyond theses stringent requirements, several additional constraints must be adequately addressed. They are related to the extended shape of the structure, the limited stability of the floor on which they are mounted, and limitations on the technology of the sensors and actuators which could couple with the electromagnets.

A dedicated control approach is proposed in this paper to meet these requirements. It includes key features to comply with the aforementioned constraints. Firstly, the instrumentation does not use any coil, magnet and elastomer, in order to be compatible with both magnetic field and radiation. Secondly, the mechatronic architecture is dedicated to support long and extended objects. Thirdly, the controller relies on a fusion of interferometric inertial sensor and force sensor, which offers unique stability properties to the closed loop system, and a high robustness against plant spurious resonances (this is especially suited as the electromagnets will be mounted on an unstable support).

While this control strategy is specifically designed for the CLIC, several of the features and components of the instrumentation are also of potential interest for the LIGO in-vacuum isolators, whose performance is currently partly limited by the sensor noise of its vertical inertial sensors at low frequency, and by the control bandwidth at high frequency [5, 6].

Section two presents the interferometric sensor (NOSE) used for the inertial control; section three presents the active isolation system, including the mechatronic architecture, the control strategy and preliminary experimental results. Section four gives the conclusion.

2 INTERFEROMETRIC SENSOR: NOSE

Fig. 1. Shows a picture of the NOSE prototype.

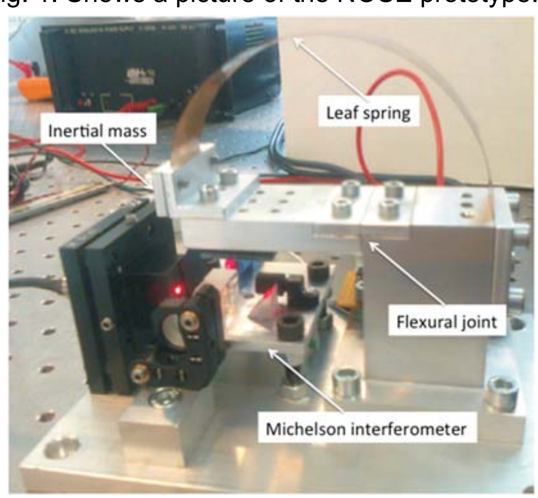

FIGURE 1. Picture of the interferometric inertial sensor NOSE.

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 balance the gravity. The oscillator is characterized by an inertial mass m=0.055kg, a main resonance frequency f_0=6Hz (tunable) and spurious resonances above 100 Hz. NOSE does not contain any loaded coil, which was found to offer several advantages, including compatibly with magnetic environments and a low thermal noise in the suspension (Brownian motion) [7].

In order to measure the relative displacement between the inertial mass and the support, a sensor based on a Michelson interferometer has developed and adapted to enable the measurement of both quadratures of the signals as described in [8].

Figure 2 shows the experimental amplitude spectral density of the interferometer noise (blue dashed-dotted line), expressed in physical units of [m/√Hz]. It has been obtained in two steps, while the motion of the inertial mass is restrained.

In the first step, we manually slightly moved one mirror in order to obtain the parameters of the Lissajous figure for the calibration.

In a second step, we have recorded the photodiode signal without disturbing the interferometer, combined with the parameters obtained from the first step in order to express the photodiode signals in displacement units, which is considered to be the sensor noise. It results in a resolution of 3 pm/√Hz above 1 Hz, and 20 pm/√Hz above 0.3 Hz [6]. Including the inertial mass dynamics, the resolution remains 3 pm/√Hz above 4 Hz (red line in Fig.2).

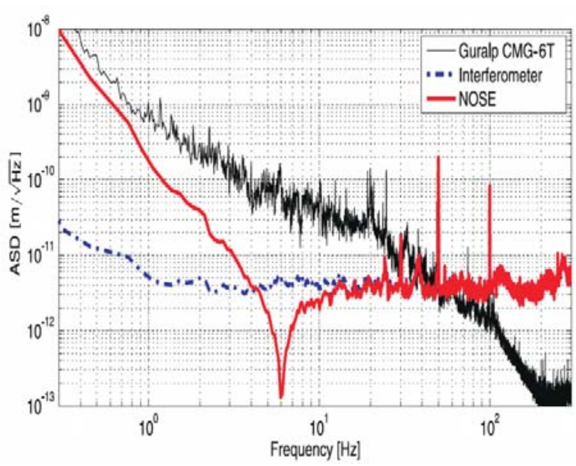

FIGURE 2. Comparison of sensor experimental resolution: Guralp CMG-6T (black line, obtained from two sensors side by side placed in a quiet environment); resolution of our NOSE interferometer, measured by blocking the inertial mass; estimated resolution of NOSE (red line) [9].

3 ACTIVE ISOLATION SYSTEM

3.1 Mechatronic architecture

In order to control the six degrees-of-freedom of a sensitive equipment, at least six actuators are required. Depending on the feedback control objective, the supports are either oriented parallel/perpendicular to the gravity [10, 11], or inclined in the manner of a Stewart platform [12]. For the final focus CLIC quadrupoles, a high authority is required in the vertical direction and a weaker authority in the lateral, yaw and pitch directions.

No authority is required in roll and longitudinal directions. Due to the extended shape of the electromagnet, it has been decided to use eight supports, as shown in green in Fig. 3: Four in the vertical direction (two at each end), and four in the lateral direction, with a small angle to restrict the longitudinal motion.

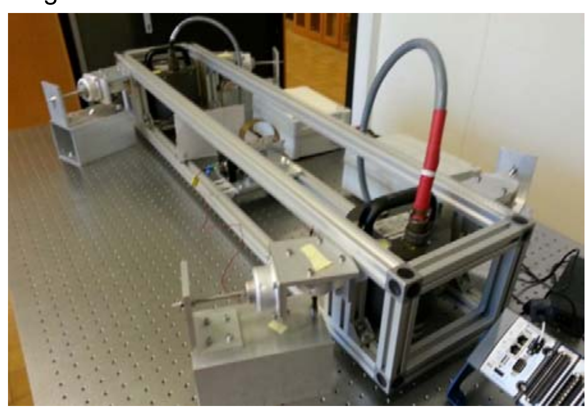

FIGURE 3. Picture of the active isolation system

3.2 Control strategy

A first concept was studied, where each leg was made of an actuator mounted in series with an inertial sensor as described in [13]. The idea was to collocate actuator/sensor pairs and use SISO decentralized controller in each mount. In this configuration, each actuator compensated the absolute motion of the quadrupole, measured in the direction of the actuator. However, this idea was rapidly withdrawn due to practical difficulties: it is not straightforward to mount an inertial sensor in series with an actuator, the configuration does not guarantee the stability of the feedback loops, and it is difficult to develop both small and sensitive inertial sensors.

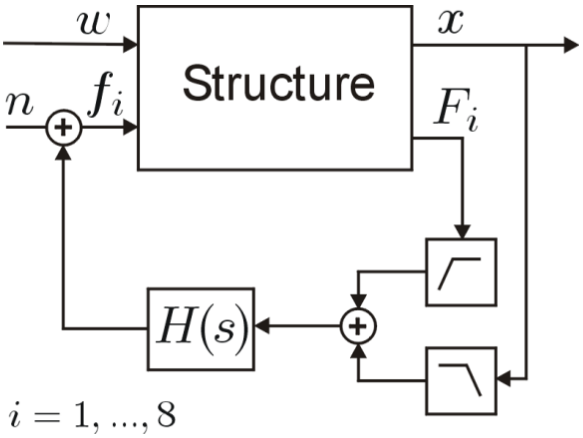

FIGURE 4. Closed loop bloc diagram. The strategy combines a centralized inertial control at low frequency, and decentralized force control loops in each active leg.

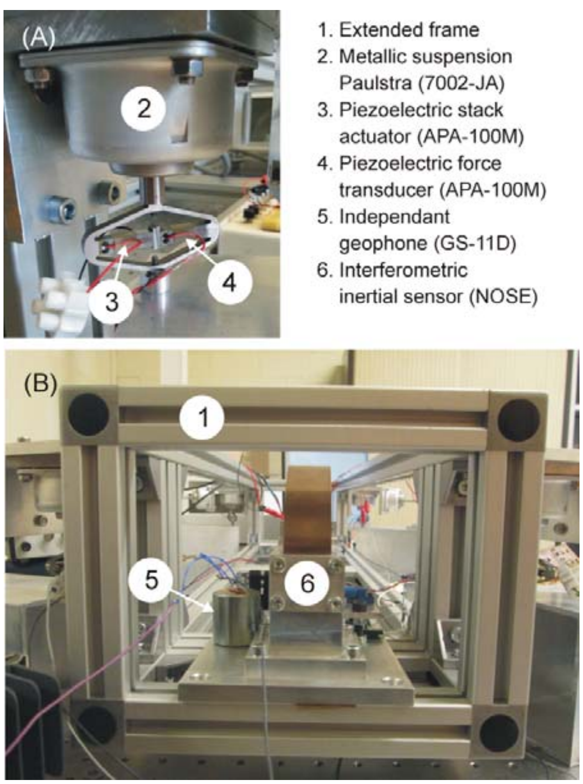

FIGURE 5. Picture of the experimental set-up. (A) One active leg, constituted of a dual pair of piezoelectric actuator/sensor, in series with a metallic suspension. (B) Picture of the interferometric inertial sensor (NOSE) used in the feedback loop, and of the witness geophone used to assess the closed loop performance.

For these reasons, we have decided to use high resolution inertial sensor [8] (NOSE presented in section 2) at low frequency for centralized inertial control and fusion the inertial sensor at high frequency with decentralized force feedback loops in each mount, as shown in Fig. 4, where *i=1,..,8*. The method has been published in [14].

In the experimental set-up, each active mount is made of a piezoelectric stack actuator APA100M from Cedrat Technologies, mounted in series with a metallic suspension Paulstra 7002-JA to offer passive isolation at high frequency (Fig.5A). This configuration offers the interesting property to be completely compatible with particle accelerator environments. Each piezoelectric stack actuator is further divided in two parts: one is used as actuator, whereas the other one is used as force sensor, the assembly making a dual truly collocated actuator/sensor pair.

3.3 <u>Experimental results</u>

The control strategy has been implemented in a Dspace DS1103 at 5kHz. For the time being, only the vertical direction has been tested. In order to remain above the noise floor of the witness geophone, random noise (*n*) is injected in the actuators, and the equipment motion is measured by a geophone (*x*).

Figure 6 shows the transmissibility between *n* and *x* when the controller is turned off (T_{off}) and turned on (T_{on}). The feedback operation reduces the transmitted motion by three orders of magnitudes. The performance is limited by the geophone noise, but not by feedback stability issues.

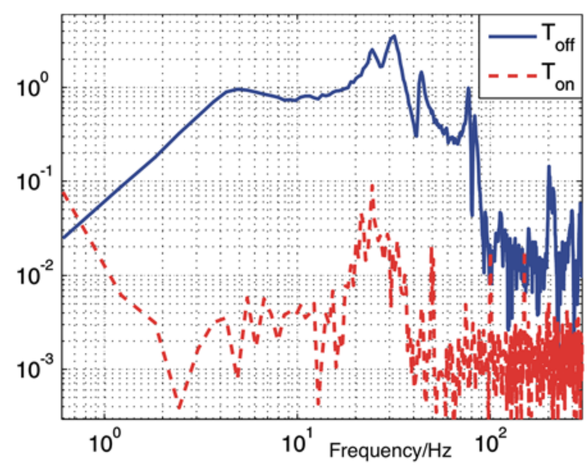

FIGURE 6. Vertical transmissibility between the noise (n) injected in the actuator and the structural vibrations measured by the witness geophone (x), integrated, and normalized, when the controller is turned off (T_{off}) and turned on (T_{on}).

4 CONCLUSION

The paper has presented preliminary experimental results of an active vibration isolation stage, dedicated to support extended payloads. To the best of the author's knowledge, this is the first active isolation system which does not contain any coil, magnet or elastomer, which makes it fully compatible with accelerator environments. Using the proposed strategy, preliminary results have shown that transmitted motion can be reduced by three orders of magnitude (60 dB) when the controller is turned on. In a future work, the closed loop performance in the lateral direction will be tested as well.

Though the inertial sensor do not meet sensor noise requirements to potentially improve the LIGO active platforms, the prototype lays out technology of interest for a vacuum compatible and magnetic insensitive vertical interferometric sensor. Additionally, the active control results demonstrate that the blend of inertial sensors and force sensors permit to achieve very large bandwidth, which is also of potential interest for the enhancement of active isolators used in gravitational wave detectors.

5. ACKOWLEDGMENTS

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REFERENCES

[1] Matichard, F., et al., *Seismic isolation of Advanced LIGO: Review of strategy, instrumentation and performance.* Classical and Quantum Gravity, 2015. **32**(18): p. 185003.

[2] Collette, C., S. Janssens, and D. Tshilumba, *Control strategies for the final focus of future linear particle collider.* Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2012. **684**: p. 7-17.

[3] Collette, C., et al., *Nano-motion control of heavy quadrupoles for future particle colliders: An experimental validation.* Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2011. **643**(1): p. 95-101.

[4] Le Breton, R., et al., *Nanometer scale active ground motion isolator.* Sensors and Actuators A: Physical, 2013. **204**: p. 97-106.

[5] Matichard, F., et al., *Advanced LIGO two-stage twelve-axis vibration isolation and positioning platform. Part 1: Design and production overview.* Precision Engineering, 2015. **40**: p. 273-286.

[6] Matichard, F., et al., *Advanced LIGO two-stage twelve-axis vibration isolation and positioning platform. Part 2: Experimental investigation and tests results.* Precision engineering, 2015. **40**: p. 287-297.

[7] Saulson, P.R., *Thermal noise in mechanical experiments.* Physical Review D, 1990. **42**(8): p. 2437.

[8] Zumberge, M., et al., *An optical seismometer without force feedback.* Bulletin of the seismological society of America, 2010. **100**(2): p. 598-605.

[9] Collette, C., et al., *Prototype of interferometric absolute motion sensor.* Sensors and Actuators A: Physical, 2015. **224**: p. 72-77.

[10] Vervoordeldonk, M. and H. Stoutjesdijk. *Recent developments, a novel active isolation concept*. in *6th euspen International Conference, Baden bei Wien*. 2006.

[11] Beard, A.M., D.W. Schubert, and A.H. von Flotow. *Practical product implementation of an active/passive vibration isolation system*. in *SPIE's 1994 International Symposium on Optics, Imaging, and Instrumentation*. 1994. International Society for Optics and Photonics.

[12] Stewart, D., *A platform with six degrees of freedom.* Proceedings of the institution of mechanical engineers, 1965. **180**(1): p. 371-386.

[13] Anderson, E.H., J.P. Fumo, and R.S. Erwin. *Satellite ultraquiet isolation technology experiment (SUITE)*. in *Aerospace Conference Proceedings, 2000 IEEE*. 2000. IEEE.

[14] Collette, C. and F. Matichard, *Sensor fusion methods for high performance active vibration isolation systems.* Journal of sound and vibration, 2015. **342**: p. 1-21.