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A LOW NOISE LASER INTERFEROMETRY READOUT FOR CHALLENGING ACCELERATION MEASUREMENTS IN SPACE

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I. INTRODUCTION

Acceleration measurements are needed to various levels of sensitivity for almost all space missions in the fields of fundamental physics, space geodesy, space exploration, as well as on the space station. Acceleration sensors have a "free" (or weakly coupled) test mass inside a cage rigid with the spacecraft, and yield their relative acceleration by reading the relative displacements (linear and angular, if needed) of the test mass with respect to the cage. The accelerations of interest require very low noise readout also at low frequencies. Typically, the displacement measurement is made with a capacitive sensor with a first armature fixed to the cage, the second one being the mass itself, which is made of, or properly coated with metal [1, 2, 3].
Laser interferometers have demonstrated to be able to measure displacements with accuracies to the level of the picometer [4] and their use is foreseen in high-resolution measurement in space [5]. Today's laser sources -such as solid state diode pumped lasers, extended cavity diode lasers or fiber lasers- can be integrated in compact subsystems suitable for space missions. In addition, a pletora of fiber integrated components (mostly coming from telecom industry) allow us to realize compact and robust interferometers which could be used in the next future in place of capacitive sensors.
We report on the development of a Laser Interferometer Gauge (LIG) designed to measure the displacement of the test mass of accelerometers for space missions. Laser interferometry readout has two advantages compared to capacitance readout. In the first place, the laser interferometer output is linear with the gap D between the test mass and the cage, while it is known that capacitance sensors readout can be linearized only for very small changes in D. Secondly the sensitivity of the interferometer readout is independent on the gap D, while in a capacitive sensor it goes as 1/D, which leads to using narrow gaps and therefore to facing the related noise sources. Furthermore, if low frequency thermo-mechanical drifts (i.e. "real" drifts) are properly taken care of, there is no increase of noise due to the laser interferometer at low frequencies. In this work a heterodyne interferometer based on a fiber coupled laser source having $\lambda \approx 1$ µm is be presented. We also report a comparison between the interferometer and capacitance readout performances in terms of noise.

II.THE INTERFEROMETER

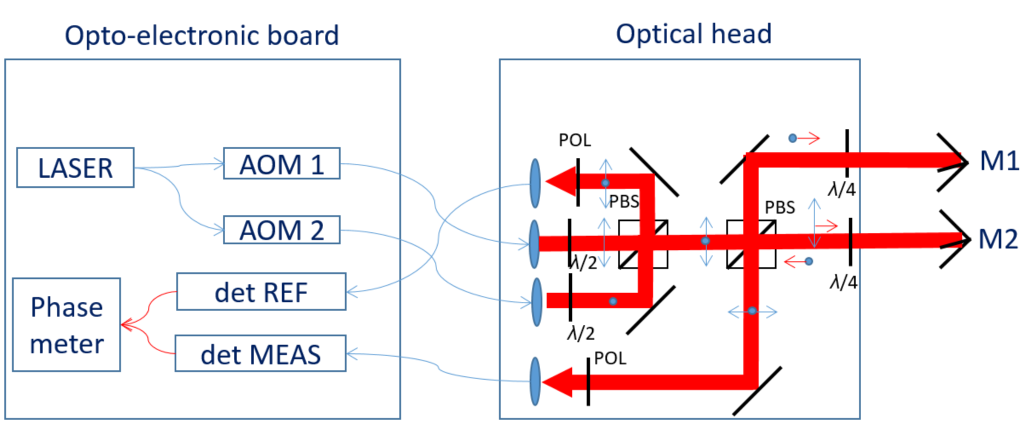

Fig. 1. Schematic of the LIG. The three units are: the opto-electronic board where the two laser beams are generated and sent to the interferometer, the interference signals are detected and the phase is measured; the optical head where the optical components are fixed; the mirrors assembly (M1 and M2) represents the distance to be measured. The blue connectors are optical fibers, the red ones are electrical wires.

A schematic diagram of the LIG is shown in Fig. 1. The laser source is a continuous-wave high performance Planar-Waveguide External Cavity Laser (PW-ECL) already successfully used within the ESA contract (No. 4000105051/11/NL/CP) COATS with wavelength λ = 1.064 μm. The laser beam is split into two parts and undergoes differential frequency shift with the use of two acousto-optic modulators (AOM1 and AOM2) to generate two laser beams having frequencies ν_2 and ν_1. The two laser beams are sent to a classical polarization separation Michelson interferometer. Here a reference signal is generated by mixing the two laser signals before entering in the interferometer and sent to the "reference" detector. The two beams are than separated and sent to the two mirrors and eventually mixed and sent to the "measurement" detector.

In Figure 2 is shown a picture of the optical part of the LIG prototype. The optical components are glued to a zerodur base.

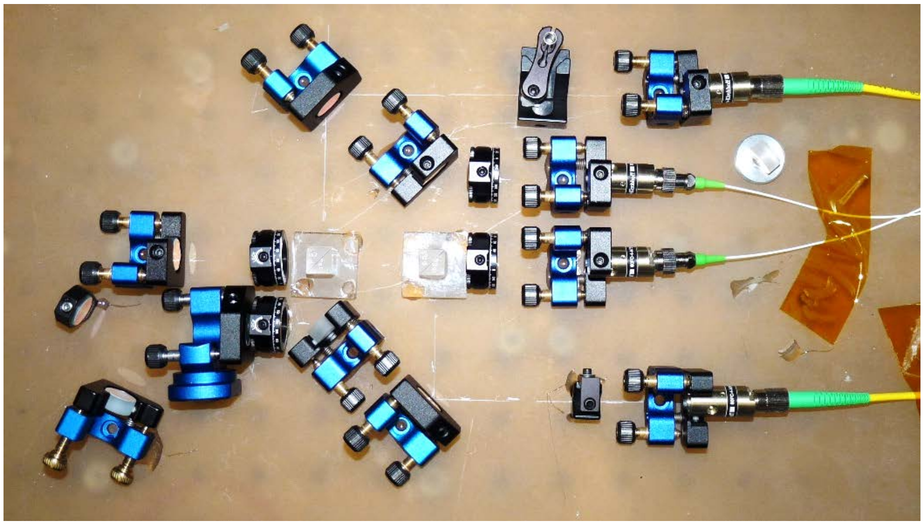

Fig. 2. Picture of the optical board and the mirrors for the stability and noise test. The two white fibers are the inputs from the laser source; the two yellow fibers are the outputs towards the detectors.

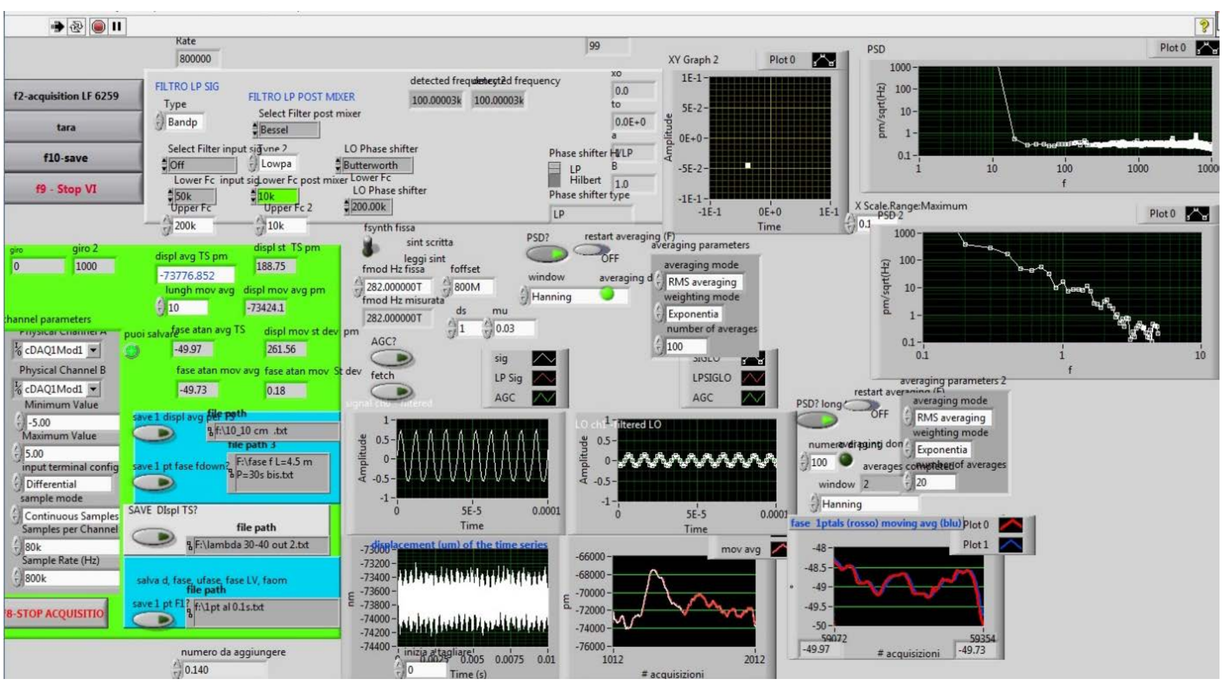

Fig. 3. Screenshot of the software used to measure the interferometer output. The phase is converted into displacement, the temporal series is recorded and the noise spectral density is calculated.

The power of the laser beams reflected on the test masses is kept as low as 1 µW in order to have a negligible effect due to the radiation pressure on the displacement of the masses. This power level, on the other hand, is high enough to guarantee the S/N level to the interferometric signal.

The two signals coming from the detectors, having frequency $\nu_2 - \nu_1 = 100$ kHz, are sent to an A/D converter and elaborated via a LabView based software which measures the phase, hence the displacement and calculates the noise spectral density of the signal. A screenshot of the front panel of the software is shown in figure 3.

III. PRELIMINARY RESULTS

The errors sources (uncertainty) of a heterodyne interferometer are due to: the electronic noise of detectors and phase meter; the cyclic error due to cross-talk between optical signals; the frequency stability of the laser source. The preliminary results are shown in figures 4 and 5. In figure 4 is shown the typical spectral noise density of the interferometer when the mirrors are fixed. The measurement is taken both with the interferometer balanced and with the interferometer unbalanced. That spectra includes all noise sources quoted above excluded the cyclic errors. In particular it can be observed that the noise at 1 Hz is close to the level of 10 pm/√Hz that was the target of our work, than we can find that at high frequencies (where the noise is limited by the electronics and shot noise) the noise level is around 1 pm/√Hz. Finally, we see that at low frequency the noise is increasing up to the level of 1 nm/√Hz at 0.01 Hz. At low frequencies there are two predominant phenomena: the first is the effect of the laser frequency stability in combination with the unbalance of the interferometer, the second is due to mechanical drifts of the components of the interferometer and effects due to the polarization rotation in the fibres. As for the laser stability we have evaluated the contribution of the effect for different unbalances taking in consideration the instability of our laser. These simulations are in figure 7, next chapter. The noise we have observed in fig. 4 is higher (also for zero unbalance) than the simulation results. We believe it is due to some unwanted random polarization rotation occurring in the fibers from the laser source to the interferometer. This point is under investigation.

In figure 5 is shown the result of a displacement measurement. One of the two mirrors is fixed to an active piezoelectric actuator and its position is modulated with a sine signal corresponding to 75 pm p.p. at a frequency of 1 Hz. The power spectral density is calculated. Two records are reported. Although the signal is well visible, the noise floor is in fact slightly higher than what reported in fig 4. The reason for that is likely the noise of the actuator itself which is measured by the interferometer.

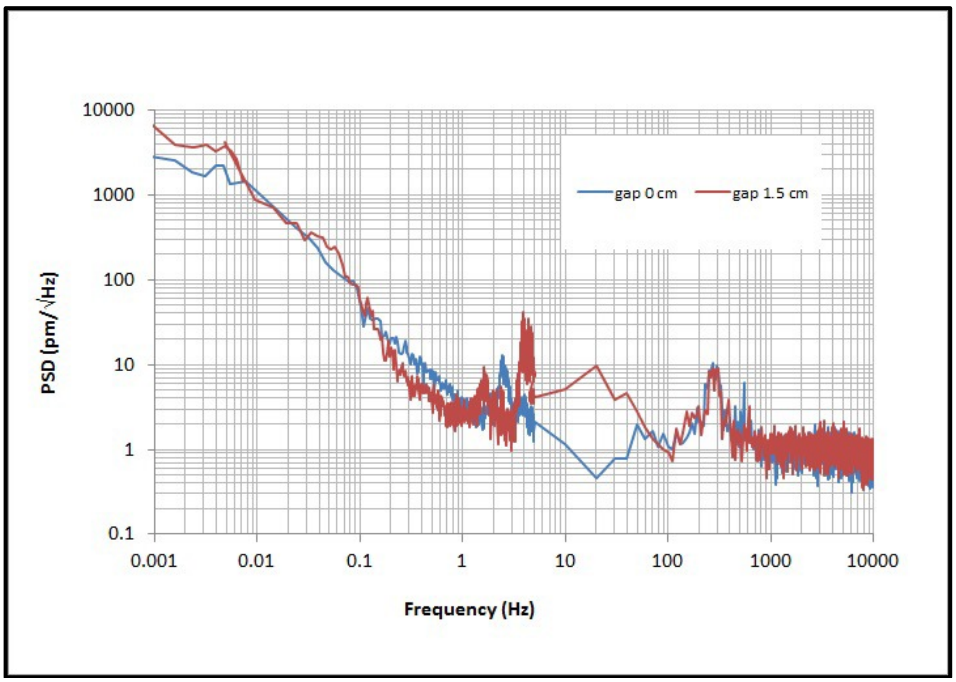

Fig. 4. Power spectral density of the interferometer output when the mirrors are fixed. The residual noise is a limit for the measurement. The two curves are taken with the interferometer balanced (blue) and with 15 mm unbalance (red). The noise is due to laser instability combined to the unbalance of the interferometer, the electronics noise, the acousto-mechanical noise of the environment and the thermo-mechanical drift of the optical components.

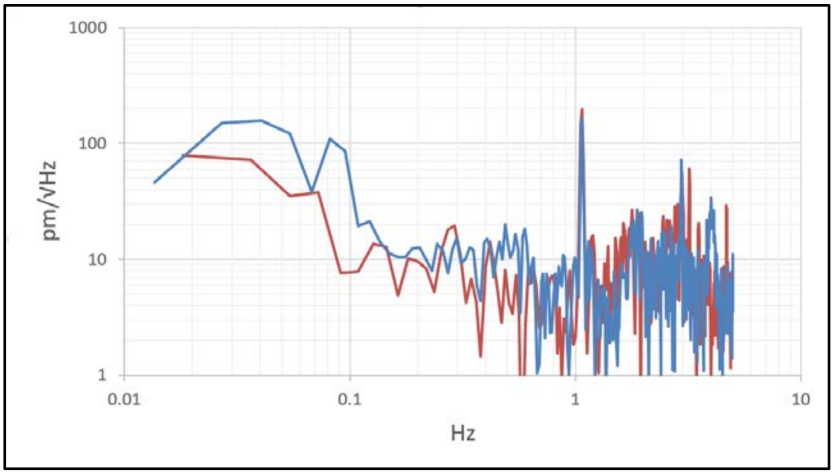

Fig. 4. Measurement of a small displacement. A piezoelectric actuator has been used to move one of the two mirrors. The power spectral density has been measured when the mirror is moved by 75 pm p.p. at 1 Hz.

As for the characterization of the nonlinearities, LIG will be tested using a high resolution actuator with sub picometer resolution developed at INRIM (figure 6) to characterize state of the art interferometers. It is based on a piezo-capacitive stage whose movement is controlled by an integrated multiple reflection interferometer. It is made of a Clearceram structure integrating a piezo-capacitive stage which moves under the control of a multi reflection interferometer. The two mirrors at the front are the test mirrors for the LIG under test.

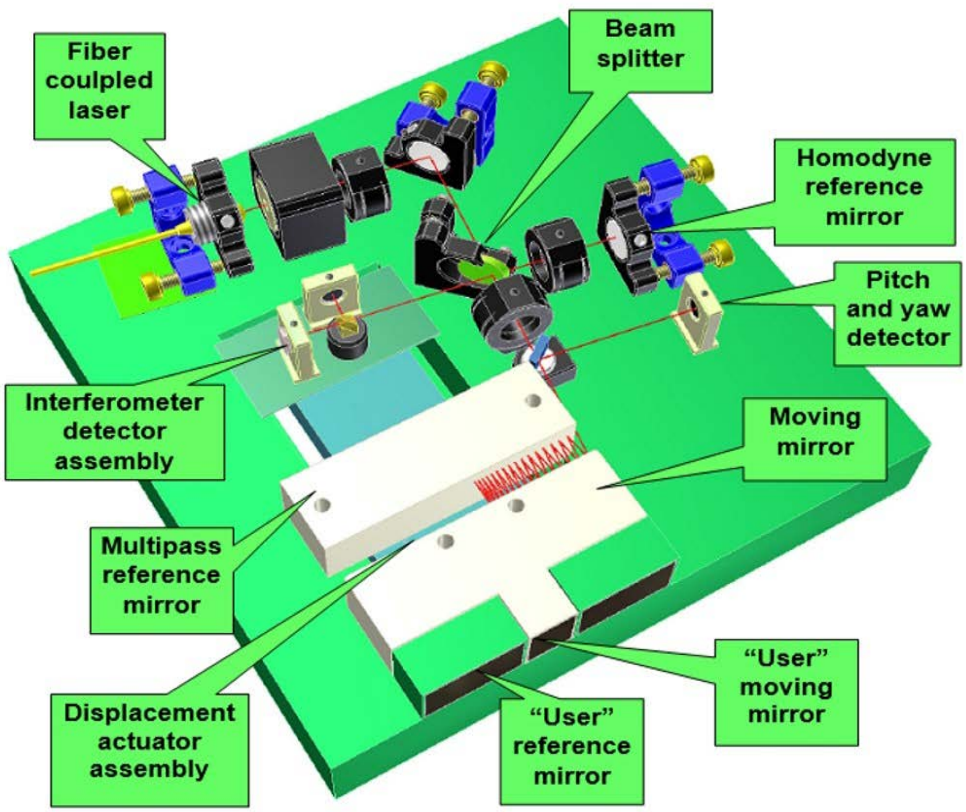

Fig. 6. The Picometer Reference Actuator (PRA) to be used to characterize LIG performances in terms of linearity and sensitivity. The actuator is based on a multiple reflection homodyne interferometer and is capable of 100 µm displacement with picometric resolution. The LIG will be placed in front of the PRA measuring the relative displacement of the reference and the moving mirrors.

IV. COMPARISON WITH CAPACITIVE SENSORS

In figure 7 we have collected the performances of the capacitive readout designed for different accelerometers for space missions [1, 2, 3] together with the theoretical LIG performance with different arm unbalances. Note that even if the final quantity to be measured is an acceleration, the sensor measures a physical displacement between the reference frame and the floating mass, so noise limit is given in m/√Hz rather than m/s^2/√Hz. The conversion displacement/acceleration obviously depends on the resonant frequency of the mass-spring system. It is evident that even in the worst case (large unbalance) the LIG has lower noise level than the best capacitive sensor.

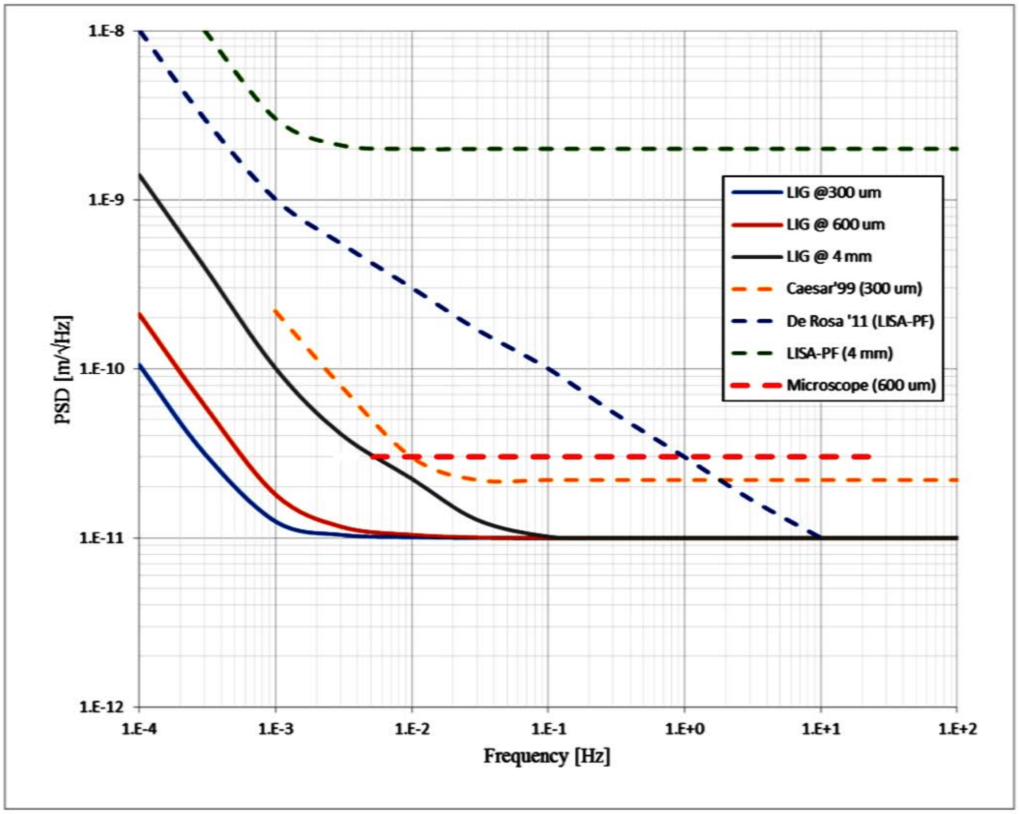

Fig. 7. Comparison between the sensitivity of the capacitive readout of the accelerometer published in reference [1, 2, 3] and the theoretical sensitivity of the LIG for different unbalance values.

V. CONCLUSIONS

We propose the realization of a miniaturized heterodyne interferometer (called LIG) to be used onboard space missions where high resolution displacement measurements are required. In particular, we believe that the interferometer could replace the capacitive readout for the measurement of the accelerometers' masses. The expected advantage is an increased resolution (10 pm/√Hz) and mostly the possibility of larger operative distances between the mass and the cage. Preliminary tests carried on by using off the shelf components, show the feasibility of the interferometer with the required resolution and noise target and the possibility of realizing a compact and lightweight measurement gauge. Furthermore, the interferometer developed in this work goes in the direction of the realization of an laser interferometer gauge for the measurement of the test masses of the Galieo Galilei (GG) mission [6] requiring a noise floor of 1 pm/√Hz at 1 Hz.

Future work will be the realization of a miniaturized version of the optical head and the integration in an accelerometer with the perspective of a test in flight.

REFERENCES AND AKNOWLEDGMENTS

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