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MINIATURE AND LOW COST FIBER BRAGG GRATING INTERROGATOR FOR STRUCTURAL MONITORING IN NANO-SATELLITES

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ABSTRACT

In this paper we present a newly developed Fiber Optic measurement system, consisting of Fiber Bragg Grating (FBG) sensors and an FBG interrogator. The development of the measuring system is part of the PiezoElectric Assisted Smart Satellite Structure (PEASSS) project, which was initiated at the beginning of 2013 and is financed by the Seventh Framework Program (FP7) of the European Commission. Within the PEASSS project, a Nano-Satellite is being designed and manufactured to be equipped with new technology that will help keep Europe on the cutting edge of space research, potentially reducing the cost and development time for more accurate future sensor platforms including synthetic aperture optics, moving target detection and identification, and compact radars. After on ground testing the satellite is planned to be launched at the end of 2015.

Within the satellite, different technologies will be demonstrated on orbit to show their capabilities for different in-space applications. For our application the FBG interrogator monitors the structural and thermal behaviour of a so called "smart panel". These panels will enable fine angle control and thermal and vibration compensation in order to improve all types of future Earth observations, such as environmental and planetary mapping, border and regional imaging. The Fiber Optic (FO) system in PEASSS includes four FBG strain sensors and two FBG temperature sensors.

The 3 channel interrogator has to have a small footprint (110x50x40mm), is low cost, low in mass and has a low power consumption. In order to meet all these requirements, an interrogator has been designed based on a tunable Vertical-Cavity Surface-Emitting Laser (VCSEL) enabling a wavelength sweep of around 7 nm. To guarantee the absolute and relative performance, two reference methods are included internally in the interrogator. First, stabilized reference FBG sensors are used to obtain absolute wavelength calibrations. This method is used for the temperature sensors in the system, which will be measured with an accuracy of ±1°C. Second, the strain sensors will be used to monitor deformation of piezo actuators (bimorph plates) in a way that temperature compensation is not required. Using FBGs on top and on the bottom of the plates, relative wavelength differences are measured. In order to have a high accuracy, inside the interrogator a fiber interferometer is used to track the wavelength change. Using this reference technology we are able to measure the (relative) wavelength difference between two FBGs well below 0.1pm.

Keywords: Fiber Bragg Grating, Interrogator, Fiber Optics, Nano-Satellite, VCSEL

I. INTRODUCTION

European space objectives include Earth Observation to monitor the health of the planet and the impacts of human activities, which are increasingly important in this time of climate change and growing industrialization, farming, mining, smuggling, terrorism, illegal immigration, etc. In addition, Europe seeks to stay on the cutting edge of space technology, both for the intrinsic benefits that technology offers in space as well as the benefits generated by the introduction of next generation technologies into the broader economic base.

The technologies that will be developed in the PEASSS project directly enable European space observation and in-space activities. The project will create a cutting edge technology based on piezo actuated smart composite panels, which can improve the accuracy and stability of nearly all Earth Observation sensor platforms. As described below, the improved pointing accuracy and potential for reduction of mechanical noise stands to improve all types of observations, from environmental and planetary mapping to border and regional observation. Furthermore, the project will advance alternative power generation in space, which stands to enable distributed sensor networks and other next generation space technologies. In addition, this new technology will help keep Europe leading in space research, potentially reducing the cost and development time for more accurate sensor platforms. Likewise, this new "smart structure" technology may provide positive economic impacts to other industries, such as its utilization to reduce noise and related fatigue in future aircraft composites.

The main objective of the PEASSS project is the development, manufacturing, testing and qualification in a space environment of "smart structures" which combine composite panels, piezoelectric actuators/generators, and next generation sensors for accurate pointing and power generation.

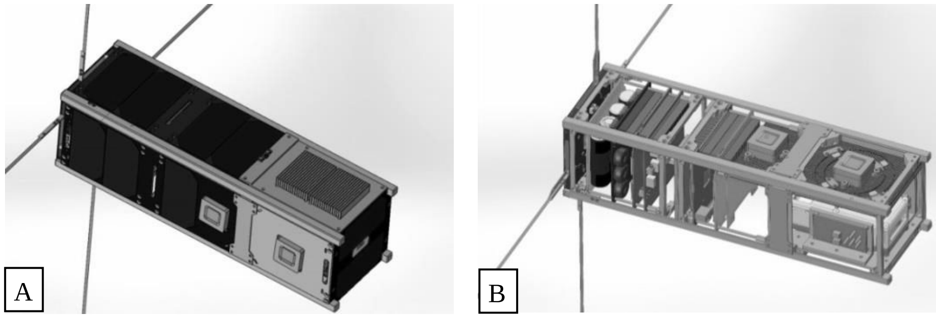

Fig. 1. Nano-Satellite model, A) outside (dimension 30x10x10cm), B) inside

The above objective can be translated into four sub-goals:

1. Demonstration and qualification in space environment of a piezoelectric actuated “smart structure” as a means of pointing an optical instrument, while correcting for thermal deformation and laying the groundwork for cancelling acoustic noise from the satellite, to achieve better accuracy than current technology, with lower mass, power use, and/or reaction time.
2. Demonstration and qualification in space environment of a piezoelectric actuated “smart structure” as a means of power generation from the pyroelectric effect, capable of generating >1 W/m2.
3. Demonstration and qualification in space environment of Fiber Bragg Grating (FBG) combined with a miniaturized interrogator, in order to measure composite structure strain levels for structure actuation control and temperature.
4. Demonstration and qualification in space environment of next generation power conditioning and data acquisition components for nano-satellites by integrating new energy scavenging methods and accommodating distributed sensor networks and novel data gathering techniques.

In this paper the FBG system and the interrogator design is explained and first prototype results are discussed. The other system payloads developed in the PEASSS project are described in reference [1].

II. FIBER OPTIC SENSING SYSTEM

A. Fiber Bragg Grating Principle

Fiber Bragg Grating (FBG) is one of the common principles of Fiber-Optic sensing. An FBG is an intrinsic sensor manufactured inside the core of the fiber itself. Inside this core of the fiber a grating is made by a lithographic-like production technology [2]. An FBG sensor is used by the principle that the grating reflects the wavelength (Bragg wavelength) of light which is proportional to the grating period (Λ) and the effective refractive index (n_{eff}) of the FBG:

$$\lambda_{Bragg} = 2 \cdot n_{eff} \cdot \Lambda \tag{1}$$

An FBG can be used as a sensor to measure strain and temperature by measuring the wavelength reflected by the FBG. The reflected wavelength will change by strain applied to the FBG (sensitivity = ~1.2pm/με) and/or by varying temperature (sensitivity = ~10pm/°C) [3]. These sensitivity values are typical for FBG sensors at a wavelength in the 1550nm band.

Using FBGs with different grating periods, multiple sensors can be addressed using one single optical fiber. In this case it is important that by applying strain and/or temperature variations the different FBG reflection peaks will not overlap in the spectral domain. An interrogator system is used to measure the wavelength responses of all the FBG sensors in one or more fibers. In Section III of this paper the interrogator design and validation is described.

B. Conceptual Design of the Optical Bench

Within the PEASSS project different technologies will be brought together. Composite manufacturing technology is used to manufacture an Optical Bench (OB) as shown in Figure 2A. On this OB, two actuators (bimorphs) are used in order to move a gimbal composed of a composite ring and a composite disc, Figure 2B. The angular movement of the ring and the disc will be around 2.5degrees in up and down direction. On both the actuators, FBGs are mounted to measure the deformation of the bimorph. The combination of the composite system, the actuators and the FBG sensors form a so-called “smart structure”. For absolute measurement of the angular movement Fine Sun Sensors (FSS) are mounted on the OB. The difference between one fixed FSS and a second movable FSS is used for (absolute) reference measurement. In addition, electrical strain gauges are also mounted on the actuators for comparison with the FBG sensors. In figure 2C, the assembled OB is shown.

In the designed system, FBG sensors are glued with space compatible EC2216 on top and bottom of both the bimorphs. One fiber containing two FBGs (FBG_1 and FBG_2) are routed over the top of both the bimorphs. A second fiber with again two FBGs (FBG_3 and FBG_4) are routed along the bottom of the bimorphs. FBG_1 and FBG_3, both on the same bimorph but in different fibers, will have the same wavelength. Also FBG_2 and FBG_4 have the same reflection wavelength. To measure the deformation of a single bimorph the wavelength difference between the top and bottom FBG has to be measured. Therefore, the common temperature and common radiation effect on the FBG have no influence on the bimorph deformation measurement. In addition, knowledge of the absolute wavelength of the lightsource at any given time during the measurement is not required.

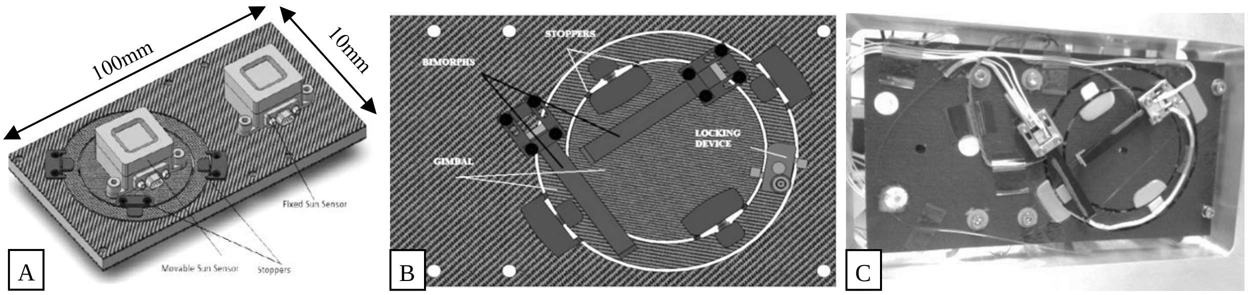

Fig. 2. A) concept design of Optical Bench, frontside, B) concept design of Optical Bench, backside, C) Assembled Optical Bench

III. INTERROGATOR DESIGN

A. Interrogator Requirements

The requirements of the interrogator are summarize in table 1. The interrogator should be able to measure at least 7 FBGs which can be multiplexed over one or more fibers. The total wavelength range of the interrogator should at least 5nm to cover all the FBG sensors. The FBG response should be measured with an repeatability of 12pm, which equals ~10με or ~1°C for a typical FBG strain and temperature sensor. Commercial interrogators have been evaluated, but no suitable device is available.

Table. 1. Interrogator requirements

Number of FBG sensors	≥ 7
Wavelength bandwidth of interrogator	≥ 5nm
Operating temperature	0 - +50°C
Storage temperature	-30 - +70°C
Wavelength repeatability	≤12pm (= ~10με, and/or ~1°C)
Mass	≤ 800grams
Volume	≤ 110 x 50 x 40mm
Power Consumption	≤ 4W
Measurement time	≤ 0.1s (≥10Hz)

The hardware used in the interrogator will not be fully space qualified but is selected to be space compatible. This means that Commercially-off-The-Shelf (COTS) components can be used, but should be analyzed to ensure possible use for future space applications. In this case, standard fibers which are acceptable to the purpose and duration of the mission will be used instead of radiation hard fibers. For lightsource, couplers, detectors and FBGs, this gives the opportunity to use cheaper and more accessible hardware in the demonstration phase. The level and rate of degradation of standard fibers which will occur during their exposure to radiation is well known. FBG sensors written in radiation hard fibers have also been analyzed by many groups [4]. The approach of standard non-radiation hard hardware is valid because of the relative small operating lifetime of the satellite. In a few weeks after deployment the system will be tested, during which the total radiation level during this lifetime is only around 5krad.

In addition, most of the selected components inside the interrogator will be vacuum compatible. Components that are not vacuum qualified will be tested to be operational in vacuum environment.

B. Interrogator Design

The interrogator is one of the payloads onboard of the satellite to perform measurements in orbit. From satellite level hardware, the interrogator will be powered by a 12V line. The power consumption of the interrogator designed is ~560mW during the measurement in operating mode and ~540mW in non-operating mode. At the satellite level, the interrogator measurement will be started by a trigger signal and the data is directly read out by two ADCs located in the interrogator. The trigger is connected to the lightsource (Vertical-Cavity Surface-Emitting Laser (VCSEL)), to start a wavelength sweep, explained in section IIIC. The response of the FBG sensors located at the optical bench is monitored by multiple photodetectors.

The optical signals are connected to ADC1 (6CHNL, sampling @50kHz, 14bit resolution). Electrical reference sensors, a pt1000 reference temperature sensor and strain gauges, are connected to ADC2, (6CHNL, sampling @10Hz, 14bit resolution). Both ADCs are connected to the satellite data handling unit interfaced by SPI bus.

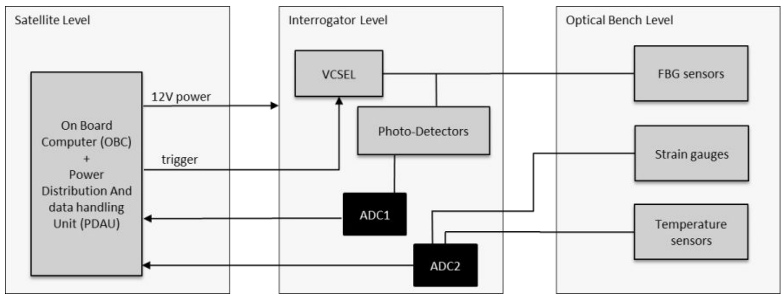

Fig. 3. System diagram

C. Interrogator Optical Design

To meet all the requirements, an interrogator principle with a wavelength tunable VCSEL has been selected. The low power consumption, small size, low cost and wavelength range are properties which all match the requirements needed. Radiation effects on VCSEL type lightsources have been analyzed [5], and tests in Thermal-Vacuum have been performed, showing promising results. The VCSEL has an output in the 1535nm range with a tuning range of around 7nm. The wavelength output of the VCSEL is tuned by varying the input current. Using an linear current sweep from 0mA to 15mA within 100ms, the wavelength output will be close to a linear wavelength sweep of 7nm range.

Figure 4 shows the schematic diagram of the designed interrogator. The output of the VCSEL is divided into 3 channels using a 3x3 coupler. Behind the 3x3 coupler, at all branches a 2x2 coupler is connected. This 2x2 coupler directs the light towards the FBG arrays and in backward direction to the PhotoDetectors (PD). PD_A will measure the response of $CHNL_A$, with PD_B and PD_C for the two others channels. In $CHNL_A$, at the inside of the interrogator, two a-thermal FBGs are connected as reference and an FBG_{TEMP_IN} to measure the internal temperature of the interrogator.

In Channels B and C, marked as thick lines, a fiber interferometer is made between the first 3x3 coupler and the second 3x3 coupler. This interferometer has the purpose of measuring the wavelength output of the VCSEL. The wavelength sweep can change (e.g. due to temperature effects) from sweep to sweep. By measuring the wavelength response during all sweeps, this can be corrected in the data analysis. The interferometer has an Optical Path Difference of around 10mm and is comprised of a 3x3 coupler and PD_{IF1}, PD_{IF2}, PD_{IF3}. Such a 3-port interferometer is a well-known configuration [6,7,8]. Measuring the phase output of the interferometer, the wavelength can be calculated as:

$$\Delta\lambda = \frac{-\Delta\varphi\lambda^2}{2\pi \mathrm{OPD}} \tag{2}$$

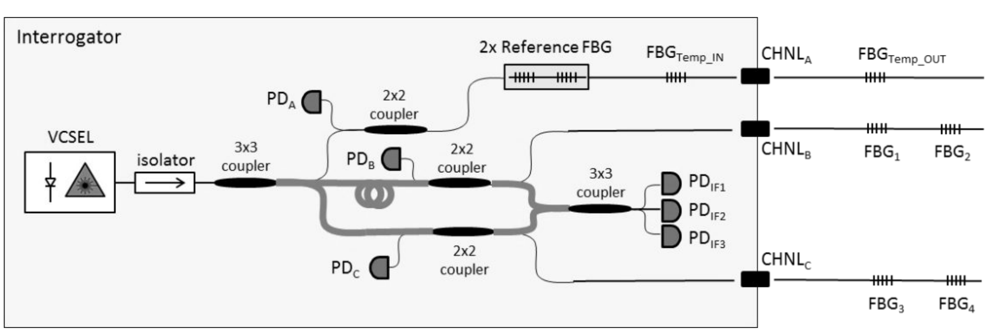

Fig. 4. Schematic drawing of interrogator

As described in Section IIB, FBG_1 and FBG_3 sensors are mounted on top and bottom of a bimorph (as are FBG_2 and FBG_4). Both FBGs on the same bimorph will have the same wavelength with the bimorph in neutral position. When the bimorph is bent up or down, both FBG peaks will be separated in the wavelength domain. By temperature and radiation effect, both FBGs will shift by the same wavelength amount. Measuring the FBG response on PD_B and PD_C by using a Gaussian fit analysis will return the peak location and separation between the two FBGs (either in sample or time). Using the interferometer data, the relative wavelength change can be calculated.

For the temperature FBG sensor (FBG_{Temp_OUT}) the same approach is used. In this case an a-thermal FBG is used as an absolute temperature and wavelength reference.

D. Interrogator mechanical design and assembly

The interrogator system has been built and functionally tested. In Fig. 5, the interrogator is shown. Three mini-AVIM connectors (space qualified optical connectors from Diamond) are the Fiber Optic connections to the FBG sensors on the OB. Above the optical connectors, a 20-pin connector is placed for power and data-interface with the satellite. On the top side, a 12-pin connector is placed for connecting the strain gauges and electrical temperature sensors on the OB. The total mass of the assembled interrogator is ~300gr.

Not all the COTS components inside the interrogator are vacuum compatible, meaning that plastic covers and coating could not be avoided. To avoid outgassing a part of the interrogator is filled using Epo-Tek 301 (NASA approved potting material for Fiber Optics).

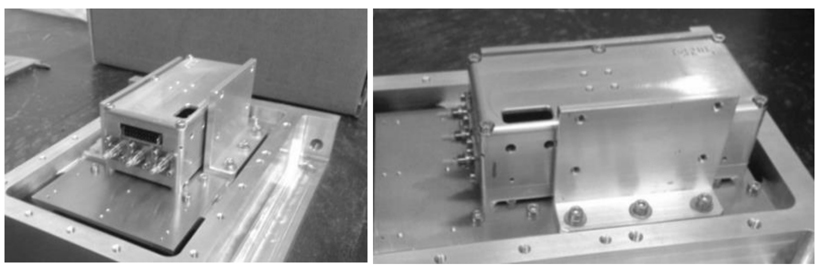

Fig. 5. Interrogator housing at interface bracket together with electronic interface brackets

IV. MEASUREMENT RESULTS

During launch or while in orbit the OB and the interrogator are exposed to specific operational environments including thermal and vibrational influences. The impact on the performance of the system or sub-systems are measured and presented in this section.

A. Interrogator performance

In order to determine the tilting angle of the smart structure, time-varying optical signals must be transformed into an angle. The accuracy which can be obtained in determining the wavelength of the FBG sensors after calibration will be translated into a tilting angle of the structure. At the time of writing the final conversion could not be made, since it requires a calibration of the final assembly, which is yet to be performed.

The planned approach is to measure the FBG peaks as a function of time while sweeping the wavelength of the VCSEL. The center position $\Delta\lambda_c$ is calculated using a Gaussian fit algorithm and the wavelength correction using the interferometer data, see figure 6.

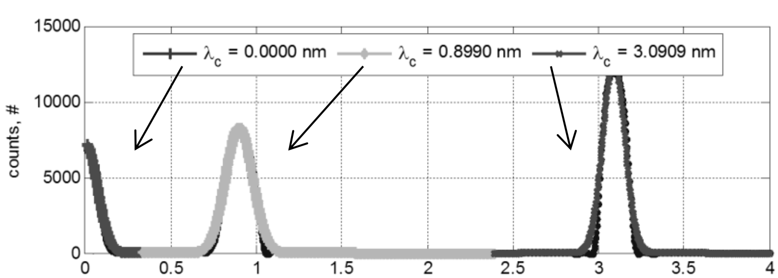

Fig. 6. FBG peak measurements

In the processing, the time separation of the sensors with respect to the a-thermal reference FBG is determined. The tilting angle of the OB can be obtained by calibration. In order to determine the repeatability of the interrogator, the variation of FBG response for 10 successive sweeps of the VCSEL at different temperatures (T_{VCSEL} = 16, 18, 20, 22 and 24°C) has been measured. A repeatability of 3.5pm is found, which is well below the 12pm that was specified by the project requirements.

An interrogator with a comparable scheme has been built as a functional prototype. Without optimization for low volume, low power consumption and a different OPD, sweep rate and electronics shows that this technology can be improved in order to a repeatability just below <0.1pm. [8]. For the PEASSS project we have optimized the FBG interrogator to reach the requirements of PEASSS.

B. Temperature measurement

The objective of the thermal vacuum test of the interrogator is:

1) Collection of data for thermal model correlation and to reduce the modelling uncertainties (beyond the scope of this paper).
2) To verify whether the provisions for cooling and heating are sufficient and in correspondence with the simulations. "Sufficient" in this respect means that the temperature sensitive VCSEL can be brought to and kept within its operating temperature range (beyond the scope of this paper).
3) To check whether the interrogator performs within specifications over the specified temperature range.

For the above-mentioned tests, a thermal vacuum chamber of 'Active Space Technologies' (AST) in Berlin has been used. The pressure inside the chamber at low pressure is ~0.1 mbar, i.e., the convective fraction of heat transfer is minimized, leaving the main contributions to conductive and radiative heat transport. For the interrogator two sources of thermal fluctuations were identified. The thermal fluctuations in its environmental conditions (1), and the heat produced by the interrogator itself due to dissipation of the electronics (2).

For the interrogator to work properly it is important that the VCSEL operates in the right temperature regime, i.e. 15 - 25°C. In order to monitor the internal temperature of the interrogator and of the VCSEL, the interrogator is equipped with a thermistor inside the VCSEL and with two reference temperature sensors attached to the inside wall of the interrogator housing. The interrogator internal temperature is measured by an electrical temperature sensor (NTC-type) and an Optical temperature sensor (a strain free FBG). During the tests the interior and the exterior of the interrogator were equipped with 9 extra pt100 temperature sensors. Two locations that are of special interest for discussion are the temperature at the light source and at the component producing the most heat.

Figure 7 shows the spectra of three FBGs for the temperatures, T = 14.12, 19.88, 25.13 and 31.37°C. These FBGs are installed on the inside of the interrogator. The two outer peaks at sample nr. 0 and 3100 shows the spectra for two a-thermal FBGs. The middle FBG is shifting to the right as a function of temperature with ~13 pm/°C. Notice that the shift is not appearing linear as function of sample nr. the reason is that the light source is not scanning linearly through its wavelengths as a function of the linear sweep we apply. Further we noticed that the temperature sensor still picks up some of the thermal expansion of the interrogator housing. The crosstalk is caused by the epoxy filled interrogator. This epoxy has also embedded the strain-free temperature sensor resulting in unwanted strain signal.

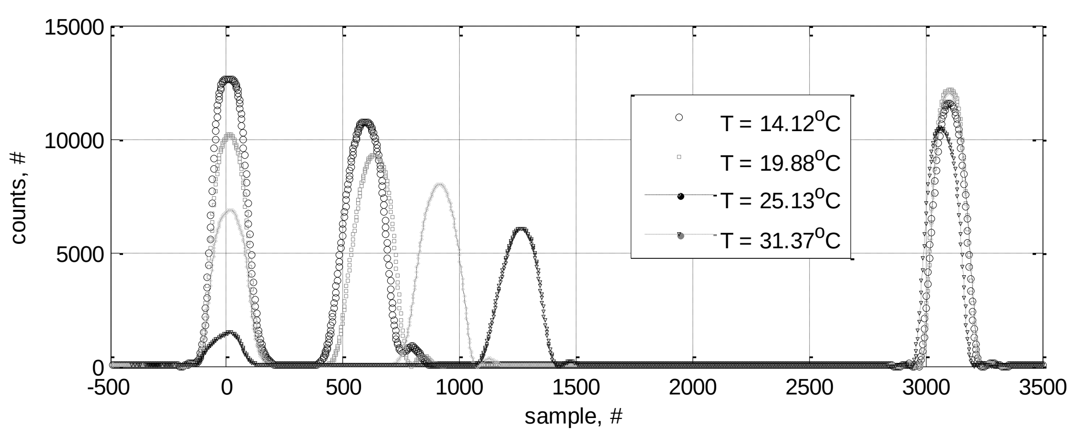

Fig. 7. Temperature measurement

C. Measurement Optical Bench performance

Using the partly assembled OB, a functional test has been performed. Using a bimorph, the composite ring was actuated. Both the FBGs on top and bottom of the bimorph were measured as well as the electrical strain gauge. Figure 8 shows the results measured using a Micron Optics SM130 interrogator. The two dashed curves represent the responses of both FBGs. They are opposite in sign as is expected. The difference between the two FBG signals are shown as the thick black line and will be used to calibrate the angular displacement of the composite ring. The electrical strain gauge measurement is shown as grey line (uncorrected) and as dotted line (corrected). A calibration factor is needed due to the presence of an unknown scaling factor in the read out system and the inaccuracy in knowing the exact location on the gauge of the bimorph. The difference between the strain measured by FBG_bottom and StrainGauge1 are shown on the right axis. Remaining error is 20με after a full curve. The remaining error and the hysteresis curve will be analyzed in the next phase of the project.

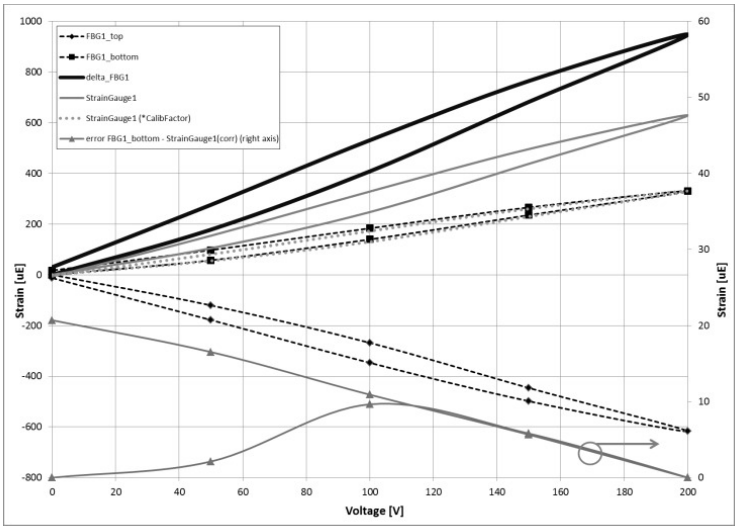

Fig. 8. Optical Bench measurement results

D. Vibration Test

During the launch of the mini-satellite the interrogator must survive vibrations. Although extensive vibration tests are scheduled, some preliminary noise vibration tests from 20Hz to 2kHz along the three axes have been carried out. In order to do so, a vibration bracket was used to mount the interrogator in anchor points mimicking those of the actual satellite.

Figure 9 shows the acceleration measured by an accelerometer on top of the interrogator in the direction of shaking. We have seen that with the low levels applied the graph can be representative for all orientations of shaking the interrogator, as well the levels on the table on which the interrogator is mounted. This means that the interrogator as well as the bracket are stiff. Notice the 22 Hz oscillation, which is a resonance frequency of the vibration setup itself.

This test is only for a first evaluation of the interrogator housing vibration response. In the scheduled vibration test, the levels will be increased up to launch levels and also the applied spectrum will be varied.

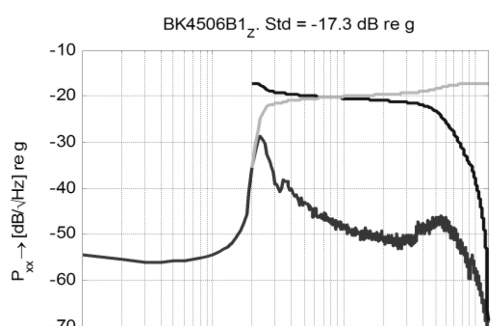

Fig. 9. Acceleration spectra

VI. CONCLUSIONS AND PROSPECTIVE

In this project an interrogator has been designed in order to measure the strain and temperature of sensors on the PEASSS Satellite Optical Bench. The interrogator meets all the requirements set at the beginning of the project. A first prototype has been built to show the performance of the system. This prototype has been tested in Thermal Vacuum to show that it is operational in such an environment. A first (low-level) vibration test was performed with the interrogator to build confidence that the hardware survives launch. In the next period a full vibration test with the hardware is planned.

At the end of this year a full flight model interrogator will be built and integrated into the satellite along with the developed hardware of all the PEASSS partners. The cubesat is planned to be launched at the end of 2015.

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