THE DESIGN AND QUALIFICATION OF THE PIEZO ACTUATED OPTICAL DELAY LINE FOR LISA-PATHFINDER-LTP

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ABSTRACT

As part of the Lisa Technology Package (LTP) on board the LISA-PATHFINDER spacecraft, the LISA-PATHFINDER interferometer is of the heterodyne Mach-Zehnder type. It requires as input two light beams derived from the same source but with a small frequency difference (a few kHz). These two optical beams are produced in the Laser Assembly (LA) via the "**Laser Modulation Unit**" (LMU). The LMU includes an optical bench, two Acousto-Optic Modulators and two Optical Delay Lines [1]. The optical configuration was designed by Oerlikon Space AG. The optical delay line is based on a triple prism, whose position is actuated by an amplified piezo actuator (Optical Path Difference Actuator - OPDA), which was designed and qualified by CEDRAT TECHNOLOGIES SA. The OPDA has a stroke of 60 µm, and a bandwidth of 10 Hz.

In order to reduce parasitic rotation effects, an elastic guided stage was designed: to save mass, the piezo actuator and the stage supporting the triple prism were machined out of Titanium alloy as a single part. FEM simulations were used extensively to optimise the OPDA design with respect to its functional specifications, its behavior under random vibrations and its thermo-mechanical deformations. The design also took into consideration the thermal mismatch between the OPDA and the optical bench which is made with Aluminium alloy.

One important issue during the qualification campaign was to monitor the metrology of the OPDA: a 10 µm change in position along the motion axis was allowed.

The present paper describes the design, and the qualification campaign of an active optical component [2], which could be used for various types of space applications.

1. BASIC PRINCIPLE OF OPERATION

The OPDA is based on an Amplified Piezo Actuator [3] which generates linear displacements. As this actuator does not provide sufficient guiding capability, a parallelogram type of flexible guide (Figure 1) is added in order to meet the requirement for very small parasitic rotations and translations. The moving stage is translated by the amplified piezo actuator, and the laser beam is reflected by the triple prism, which is fastened to the moving stage (Figure 2). The stroke of the piezo stage is 60 µm, resulting in an optical path variation of 120 µm. The design is absolutely stick-slip free, except for piezo hysteresis, which can be recovered by using a closed loop control system. The resolution is limited by the signal to noise ratio of the drive electronics; a resolution of 4 nm is thus expected, limited by the 16 bit Digital to Analog converter of the command electronics.

Because of the non-magnetic requirements of the LMU, the guiding and amplification structures are made from a Titanium alloy. As the optical bench is made with an Aluminium alloy, in order to minimize the unit's mass, thermal mismatches can arise between the OPDA and its supporting structure. It is therefore necessary to use:

- curved blades to prevent any buckling effects,
- a decoupling structure between the fixation pads.

The detailed shape of the curved blades was optimized using Finite element analysis.

The OPDA is fixed to the optical bench by a set of fixation screws. As part of the design justification, it was necessary to perform a worst case analysis to show that the friction forces at the interfaces would be sufficient to prevent bolt slippage, even in the micrometer range. This was one of the most important and challenging aspects of the qualification campaign.

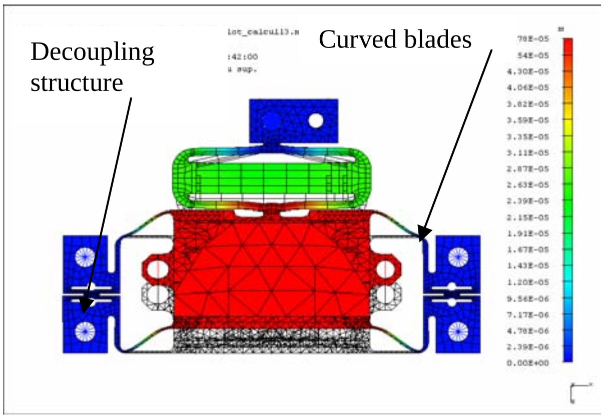

Figure 1 : Finite element model of the OPDA (strain effects have been exaggerated)

Proc. '12th Euro. Space Mechanisms & Tribology Symp. (ESMATS)', Liverpool, UK, 19–21 September 2007 (ESA SP-653, August 2007)

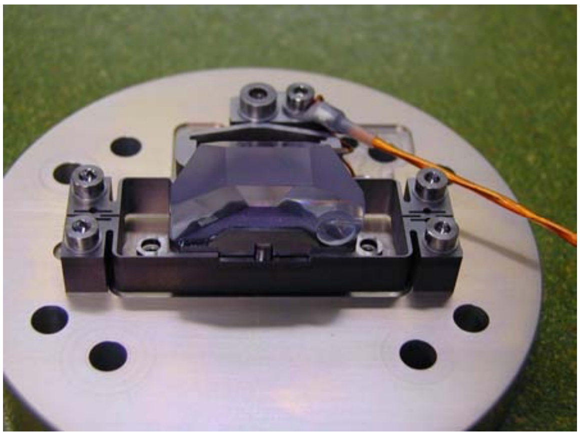

Figure 2 : View of the piezo actuated delay line OPDA supporting the triple-prism

2. DETAILED DESIGN

The detailed design includes stress analysis and worst case analysis for slippage effects at the optical bench interface. Moreover, the design needed to be robust with regard to mounting / dismounting sequences.

2.1. Modal analysis

Since random vibrations often represent the most critical environmental case for piezoelectric devices, modal analysis was performed with the Finite Element Model of the OPDA. The stiffness of the piezo actuator was adapted to the mass of the triple prism (20 gr.), in order to ensure that the first vibration modes would occur at a frequency greater than 1200 Hz.

The two first vibration modes (Figure 3, Figure 4) correspond to translations of the stage along the Z (active) and X (transverse) axes respectively.

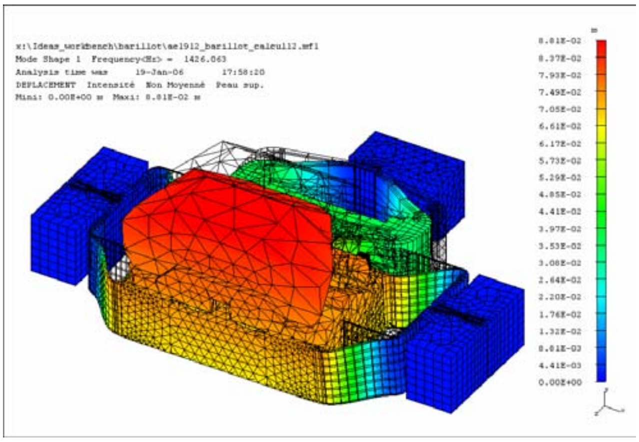

Figure 3 : Z translation mode

2.2. Stress budget

From the modal analysis and the random input vibrations spectrum, a stress budget can be computed for the OPDA, by using a normal mode expansion method.

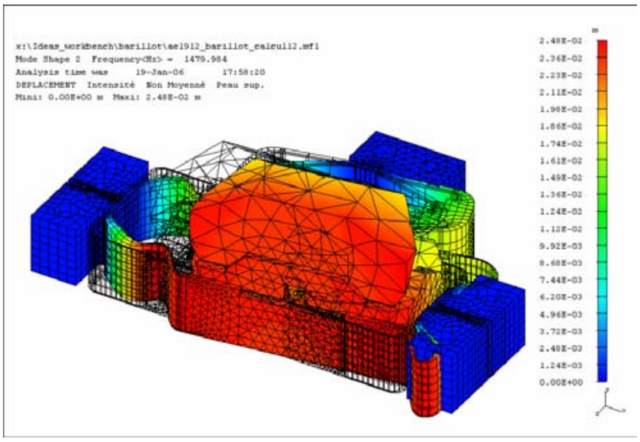

Figure 4 : X translation mode

Additional stresses budget contributors were added to account for:

- thermo-mechanical effects,
- induced torques coming from the mounting operations,
- prestress of the piezo component.

2.3. Exported vibrations

For the LTP mission it is very important for the OPDA to avoid generating micro-vibrations in the spacecraft. The exported vibrations were computed for the worst case (highest stroke and bandwidth), resulting in a maximum expected level of 6 mN.

2.4. Mounting / dismounting operations

The OPDA design was also required to be robust with respect to mounting / dismounting sequences. For instance, the position of the OPDA relative to the optical bench should not change by more than a few micrometers, during a mounting / dismounting sequence of the triple-prism. Therefore, the effects of induced torques were analysed with the Finite Element Model.

2.5. Slipping effects

The OPDA is fixed to the optical bench by means of a set of titanium alloy screws and brass based helicoils.

The first limitations of the design could indeed arise from possible slippage effects between the OPDA and the optical bench. A worst case analysis was conducted, using the following friction coefficients:

- OPDA / optical bench : 0.15
- Ta6V screw / helicoil : 0.40
- Screw head / OPDA : 0.40

The worst case screwing torque was applied and the minimum slipping force was considered. The single rear ChC M4 screw was the first limitation: in the worst considered case, the OPDA was expected to slip under a lateral force of 155 N.

3. QUALIFICATION CAMPAIGN

3.1. Lot Acceptance Test and lifetime test

As part of a qualification campaign, Destructive Part Analysis of piezo components is generally required [3]. It was verified that the piezo component does not display large cracks or significant porosity (Figure 5).

The two OPDAs were submitted to a lifetime test, with a 2 month duration. It was verified that the position of the OPDA versus the optical bench did not change during this test.

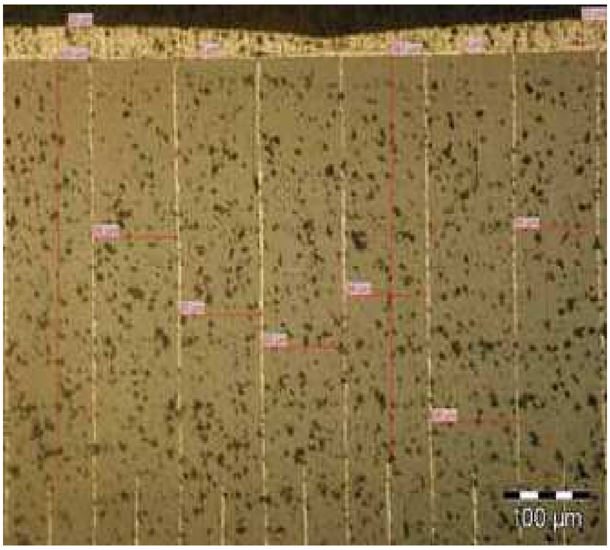

Figure 5: Sectional view of the piezo component

3.2. Random vibrations

The OPDA was subjected to a random vibration excitation of 27,4 Grms along all three axes (Figure 6). A miniature 3-axis Endevco 23 accelerometer was fixed onto the triple prism.

Extremely high quality factors (between 300 and 600) were observed along the X axis. For this reason, the recorded vibration levels on the triple prism were slightly higher than expected in the design. Nevertheless, the behaviour of the OPDA remained safe and its position did not change. It was concluded that the worst case analysis must have included a certain degree of margin with respect to the friction coefficients.

3.3. Thermal vacuum test

The last test during the qualification campaign was the thermal vacuum test. Two storage cycles were conducted between –20 and 65 °C, and 6 operational cycles were simulated between –5 and 45°C.

4. METROLOGY

A metrology campaign was carried out between each set of qualification tests, and comprised two sets of measurements along the 6 degrees of freedom:

- position of the OPDA versus the optical bench,
- position of the triple prism versus the OPDA.

The capability of a optical 2D Measuring Machine and a 3D Coordinate Measuring Machine (CMM) were combined for that purpose (Figure 7). The small size of the OPDA was a challenging aspect of the metrology campaigns, the results of which are shown in Table 1:

- it was verified that the OPDA did not move by more than 10 µm along the actuation axis (Z),
- the positional reproducibility following mounting / dismounting operations was found to be close to 20 µm and 0.01° for linear and angular displacements, respectively.

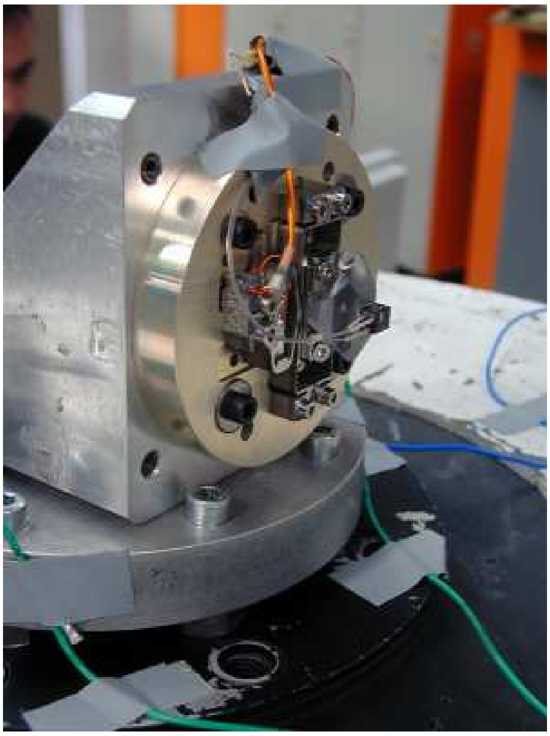

Figure 6 : View of the OPDA during the random vibration test (X axis)

Moreover, it was verified (Table 1) that:

- the triple prism can be mounted and dismounted without affecting the position of the OPDA,
- the OPDA can be mounted / dismounted onto the optical bench with an accuracy of the order of 10µm / 0,08°.

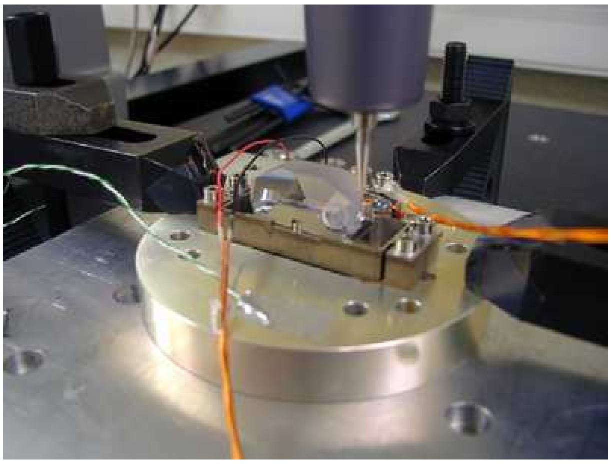

Figure 7: Metrology of the OPDA

This reproducibility lies in the range of the Measuring Machine accuracy, and is far better than that required for the triple prism position; this performance eases the alignment procedure at the Laser Modulation Unit level.

	Tx	Ty	Tz	Rx	Ry	Rz
Initial ref. value	38.015	9.09	5.99	90.009	179.885	89.994
Triple prism mounting	38.020	9.09	5.991	90.006	179.89	89.993
Triple prism dismounting	38.021	9.091	5.988	90.008	179.867	89.994
After dismounting	38.020	9.091	5.972	90.013	179.926	89.998
Payload mounting	38.015	9.09	5.973	90.008	179.945	89.996
Metrology at 45°C	38.015	9.092	5.976	90.007	179.94	89.994
Final value	38.018	9.09	5.975	90.008	179.939	89.995
Max. change	6 µm	2 µm	18 µm	0,007°	0,078°	0.005°

Table 1: Metrology records of the OPDA (rotation in °)

5. LESSONS LEARNED

Although piezo actuators, used for scientific or optical instruments in space applications, have become a mature technology in the last 10 years, several new aspects have been learned during this qualification campaign:

- piezo technology still remains new for space mechanisms: it is essential for ESCC standards to be used in setting acceptance criteria, both for the design rules and the incoming inspections [3],
- metrology reference points should be included in the detailed design, and accessibility of the 3D CMM to the device should be verified on the CAD assembly.
- some design margins should be kept for the random vibrations, even though the conventional assumption is based on quality factors equal to 100: this is especially true for modes involving monolithic elastic guiding; the ECSS design margins are not sufficient for this type of mechanism,
- the friction interface should be reproduced at the mechanism qualification level, to verify the slipping limits and to check that tightening torques do not pose a problem during installation of the mechanism. LAST BULLET POINT SHOULD BE CLARIFIED

A total of seven OPDA mechanisms have been integrated and tested. Their functional and modal behaviours are accurately predicted by the Finite Element Model. Only very minor differences were noticed between the seven OPDAs. This robust and accurate Piezo-Actuated Optical Delay Line component could be used in many new space applications, in particular those requiring the accurate and fast control of an optical interferometer.

References	Unit	OPDA60S
Notes		-
Active axis		*TZ*
Max. No-load displacement [Tz]	*µm*	*60*
Max. parasitic rotations [Rx, Ry]	*µrad*	*25*
Voltage range	*V*	*-20 ... 150*
Resolution	*nm*	*6*
Heigth (Z axis)	*mm*	*42,0*
Dimensions	*mm*	*66 * 10*
Mass	*g*	*40*
Unloaded resonance frequency (in the actuation's direction)	*Hz*	*1850*
Loaded resonance frequency (in the actuation's direction) load = 16 g	*Hz*	*1450*
Capacitance (per electrical port)	*µF*	*3,15*
Temperature range	*°C*	*-20 -60*
Random level	*Grms*	*27*

Table 2 : Summary of OPDA performances

6. REFERENCES

[1] G. Heinzel et al., ‘Interferometry for the LISA technology package LTP : an update’, J. of Phys. : Conference series 32(2006), 132-136

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