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Ultra stable iso-static bonded optical mount design for harsh environments

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***Abstract*—Through the years many stable optical mounts have been designed, analyzed and tested at TNO. This paper gives an overview of the design principles used. Various examples are presented together with verification test results.**

The use of adhesives in combination with an iso-static mount design allows mounting of optical components in a limited volume with limited deformation of the optical surfaces due to thermal and mechanical loads. Relatively large differences in thermal expansion over large temperature ranges can be overcome using a simple and predictable design at reasonable costs. Despite adhesives have limited dimensional stability and loadability, stable optical mounts can be realized when proper design principles are used.

Keywords: optical mount design, optomechanics, adhesives, cryogenic environment, pointing stability, wave front error

I. Introduction

Optical mount design for harsh environments is demanding because of conflicting requirements. On one hand the mount with bonded optics must be robust and strong to survive the launch loads and space environment. This is complicated because generally optical components are made from glass. The strength of glass depends on the random distribution of surface flaws in relation to regions under stress. Fracture of the glass occurs due to uncontrolled crack growth of these flaws under tensile stresses. This results in failure stresses that are much lower than those for metals. The adhesives used to bond the optical component to the mount has nonlinear material behavior combined and a low strength level compared to metals. On the other hand the mount must not damage or distort the optical components. This limits the forces and moments which can be applied by the mount on the optical component. Requirements for optical mount design can thus be divided between strength and performance requirements.

A. Strength requirements

The mount must be designed such that the optics survives:

- A quasi-static design load (usually in the order of 50 g to 90 g) accompanied by a random base PSD (from 20 Hz to 2 kHz) with levels up to 30 g RMS.
- A survival temperature range. A minimum range found in space applications is -50°C to +50°C. For cryogenic missions temperature goes down to 100K or lower.
- An operational temperature, which can be far below the assembly temperature for cryogenic instruments.

B. Performance requirements

Mount performance requirements are driven by higher level optical performance requirements on the instrument and include:

- Allowable wave front error (WFE) of the optics, typically in the order of tens of nanometers. Bending moments and forces on the component must be minimized to avoid deformation of the optical surfaces.
- Stability of the optical component relative to the mount interface. This includes the temporary or permanent change in position of the optical component after initial alignment due to changing gravity direction and temperature. Important also are residual effects due to hysteresis or interface slip after vibration loads or thermal loads. For stability under changing temperature and/or changing gravity conditions a well-placed thermal center and high natural frequency are important.
- Limited induced stress in the optical components to avoid stress birefringe (only critical for polarization sensitive instruments).

As demonstrated in [3] the stability and wave front error of mounted optics strongly depend on the mount design. In this paper, a simple and predictable design approach is demonstrated which shows excellent stability and low WFE while it is still capable of surviving severe loads. Examples are given which are supported by analysis and test results.

II. ISOSTATIC BONDED OPTICAL MOUNT DESIGN

Optical components usually have a different coefficient of thermal expansion (CTE) compared to the mount. For example, fused silica has a CTE of 0.5 ppm, while aluminum has a CTE of 23 ppm. To overcome the survival and operational temperature differences with respect to its assembly temperature, the mount design must be insensitive to a change in temperature (athermal design). Two different design approaches are commonly followed. An athermal design can be achieved by dimensioning the bond thickness such that expansion of mount, adhesive and optical component are matched, or it can be achieved by introducing elastic elements in the mount. Both approaches are shown in figure 1.

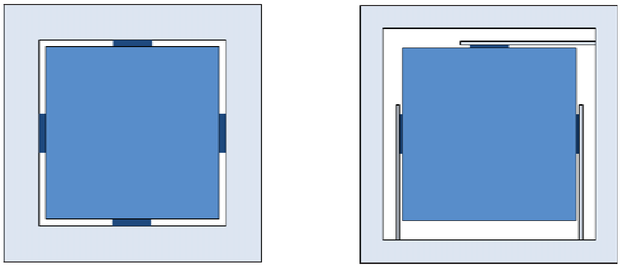

Fig. 1. Athermalization by CTE matching of the bond thickness (left) versus athermalization by applying elastic elements integrated in the mount (right).

A. Athermalization by tuning the bond thickness

This approach relies on compensating the expansion of optics and mount with the adhesive by tuning the bond thickness. A first order approximation for the bond thickness tbond as function of the size of the optics Doptic and CTE's of mount, optic and adhesive is given by equation 1. More elaborate calculation methods can be found in literature [7][8].

$$t_{bond} = D_{optic} \frac{\alpha_{mount} - \alpha_{optic}}{\alpha_{bond} - \alpha_{mount}} \quad (1)$$

In subsequent iterations (usually with a numerical model in FEM) the effect of incompressibility of the bond and the dependence of the CTE and Young's modulus on temperature must be included. This design approach often results in thick bond lines. This is not beneficial for strength and stiffness of the bond. Furthermore it is usually difficult to match the CTE's of all materials over a large temperature range, especially when considering the unavailability of reliable CTE data. The stability of this design depends on the symmetry of application of the adhesive and on the material stability of the adhesive. If the CTE match is not optimal then internal stresses arise in the bond and optical component, resulting in reduced stability and increased wave front errors.

B. Athermalization by isostatic flexible elements

A better approach to athermalize the mount is by introducing flexible elastic elements in the mount [5][6]. A very simple flexible element is the leaf spring (figure 2).

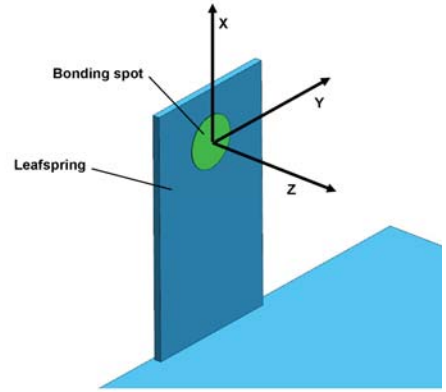

Fig. 2. Leaf spring with bonding spot.

Dimensioning is straightforward using equations 2 and 3, where k is the stiffness, E is the Young's Modulus of the leaf spring and l, t and h are the thickness, height and length respectively.

$$k_{tensile,x} = \frac{Eth}{l} \quad (2)$$

$$k_{bending,z} = \frac{Eht^3}{l^3} \quad (3)$$

When properly dimensioned, the tensile and lateral stiffness are much higher than the bending stiffness (as a rule of thumb a ratio of 1:1000 is achievable). The leaf spring can be manufactured with conventional inexpensive milling. Alternatively it can be manufactured using wire EDM.

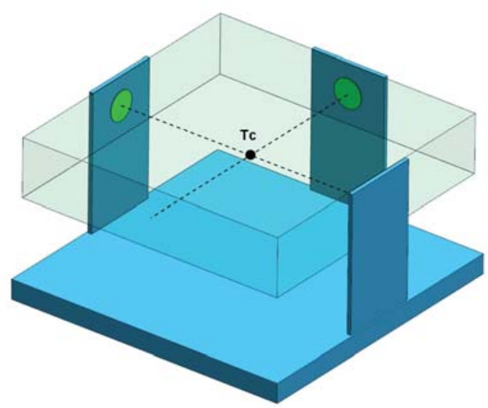

Fig. 3. Isostatic arrangement of three leaf springs around a component, showing the location of the thermal center [4].

A rigid optical component has 6 degrees of freedom (DOF). An isostatic design means that each degree of freedom is constrained only once. A leaf spring constrains X, Y and RZ with high stiffness (in the local coordinate system in figure 2). Because a bond spot has high shear stiffness, but a low torsional stiffness the combination of bond spot with a leaf spring only constrains X and Y with high stiffness. By arranging three leaf springs around the optical component as shown in figure 3, the optical component is constrained once in each degree of freedom. Because of the isostatic design the mount cannot impose significant forces or bending moments on the optics and deform the optical component. In practice true kinematic constrains do not exist and bending moments due to parasitic stiffnesses can have a second order influence. Wave front errors introduced by these parasitical forces must be checked by hand calculations or FEM analysis.

The natural frequencies of the mount are high because each degree of freedom of the optical component is constrained with high stiffness. This is beneficial for the stability of the component under inertial loads (such as gravity).

The arrangement of the leaf springs determines the location of the thermal center. If a temperature difference occurs between component and mount, the center of expansion is at Tc. Because of the flexures, the thermal expansion difference between component and mount can be large without significant effects. Usually, the thermal center is located on the optical axis.

The leaf springs decouple thermal expansion of the component in the lateral direction. Only residual local stresses in the glass arises around the bond spots. The effect of these remaining local stresses can be predicted by a FEM model of the bond spot in combination with an accurate material model of the adhesive.

Common adhesives used in optomechanical applications include room temperature vulcanization silicones (RTV) and epoxy's. The advantage of RTV's is its compliance which allows bonding materials with completely different CTE's over large temperature ranges. The advantage of epoxies is the higher strength and stiffness. TNO developed analyses tools and material models to select the proper adhesive and optimize the adhesive spot geometry. These models and tools are the key in developing highly stable optical mounts with low WFEs. By optimizing the bond thickness and diameter, local stresses in the optical component can be minimized [1].

III. APPLICATIONS OF ISOSTATIC BONDED OPTICAL MOUNTS

In this chapter a few implementations of the iso static bonded concept are described including test verification results of critical requirements (stabilities and WFE's).

The first application is the mount design for the TROPOMI instrument. Angular stability after launch loads and thermal loads are design driving in this application.

The second application is a cryogenic mount for the GAIA Wave Front Sensor. Again stability and WFE are design driving but now not only in combination with vibration loads up to 30.2 g RMS but also in combination with an operational temperature range from 130 K to 200 K.

The last application described is a scan mechanism for gravitational wave detection; Piston stability of the mechanism and mirror mount are in this application design driving, in combination with microradian stability over its lifetime. From the test results it can be seen that picometer stabilities of the mount over hours are possible with an iso static bonded mirror mount.

Currently for the EUCLID mission an iso static bonded mount is designed; low WFE, high stability and cryogen temperatures in combination with launch loads are design driving in this application. Since no hardware and test data is available yet this design is not described in detail in this paper.

A. TROPOMI optical mounts

1) Introduction

The TROPOspheric Monitoring Instrument (TROPOMI) is an advanced absorption spectrometer for Earth observation, developed in the Netherlands under contract to NSO and ESA in the frame of the ESA GMES Space Component Program. It is a push-broom instrument that combines a very large field of view with a spectral range encompassing UV, VIS, NIR and SWIR bands. It is scheduled for launch in 2015 [2].

2) Mount design

The instrument consist of an aluminum optical housing which contains more than 20 fused silica and silicon lenses. Most lenses are about 70 mm x 70 mm in size. The compact optical layout of the spectrometer channels limited the design envelope for the mount design. Therefore, all lenses are bonded to three iso-static leaf springs. The leaf springs are an integral part of the aluminum optical mounts.

For two lenses a slightly modified design was chosen because of their larger size of 95 mm x 95 mm and high mass. A fourth leaf spring was added in order to have sufficient bond area and to raise the lowest resonance frequency to above 800 Hz. Although this is not a proper iso-static design (because of the fourth leaf spring), analysis showed the effect of overconstraining the optics can be tolerated for these lenses.

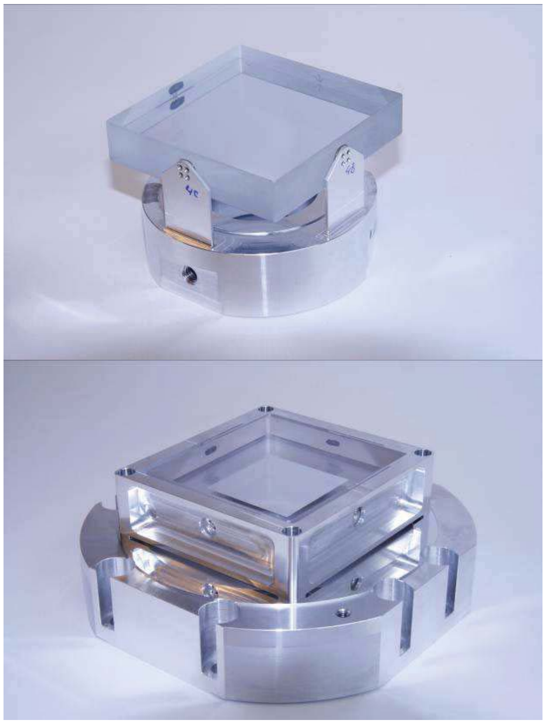

Fig. 4. Breadboards of the TROPOMI mount baseline showing three aluminum leaf springs bonded to a fused silica component (above) and four aluminum leaf springs bonded to an fused silica component (below). The thick baseplates contains a diamond turned reference for interferometric stability measurements. The dark bond spots are clearly visible. Please note the optical components are different in size, the magnification of both photos is different.

3) Verification by test

Both mount designs were breadboarded with representative lens dummies. Each breadboard included a diamond turned reference for measuring the stability of the component relative to the mount. The mechanical integrity and the stability were confirmed by subjecting the breadboards to

- Random vibration testing (with a g RMS level of 14.4 g^2/Hz)
- Eight thermal cycles in LN_2 between -50 °C and +45 °C

Before and after each environmental test the bond spots were inspected with a microscope to verify the mechanical integrity. The tip/tilt stability of the component relative to the mount reference was measured with a Zygo Fizeau interferometer. No mount showed mechanical degradation. Measured stabilities for the three leaf spring design can be found in table 1. Testing of the four leaf spring design for larger components was ongoing when writing this paper.

Component tilt of the three leafspring design with respect to the mount reference (µrad)				
Mount #	After bonding	After vibration testing	After thermal testing	**Stability over complete test**
1	48.76	45.26	48.73	**0.03**
2	211.03	217.13	211.42	**-0.39**
3	15.16	11.75	13.89	**1.27**

Table 1. Tilt stability before and after environmental testing of the TROPOMI three leaf spring mount design. Note: The few micro radian difference after vibration testing is caused by the measurement setup.

B. GAIA WFS cryogenic mount.

Fig. 5. Flight model of the GAIA wave front sensor.

1) Introduction

The ESA Gaia mission is a successor to the ESA Hipparcos mission. It’s ambitious objective is to create the largest and most precise three dimensional chart of our galaxy by providing unprecedented positional and radial velocity measurements for about one billion stars in our Galaxy. Each of its target stars will be monitored about 100 times over 5 year, precisely charting their distances, movements and changes in brightness. It is expected to discover hundreds of thousands of new celestial objects, such as exoplanets and failed stars, GAIA should also identify tens of thousands of asteroids. Gaia is being built by Astrium EADS. The mount descripted here is used in the design of the wave front sensor that TNO has built for this mission. This Wave Front Sensor will be used to monitor the wave front errors of the two GAIA telescopes mounted on the GAIA satellite. The wave front errors may be corrected by a 5-DOF mechanism incorporated in the GAIA telescopes, which also function in orbit. The GAIA-WFS will operate over a broad wavelength (450 to 900 nm) and under cryogenic conditions (130 K to 200 K operation temperature). For details see [9]

2) Requirements

The design driving requirements for the mount:

- Deformation of the surface of the mirror <3 nm RMS and 79 nm Peak to Valley in the operational range of 130 K to 200 K.
- Tip/tilt stability (RX,RY) of the mirror with respect to the structure better than 50 µrad over its life time. This included launch loads up to 30.2 g RMS and thermal cycling in the range of 100 K to 350 K.

3) Mount design

The mirror is isostatic mounted by three tangential leaf springs. The thermal center coincides with the center of gravity of the mirror. The leaf springs minimizes bending moments out of the plane of the mirror, this results in a low global WFE of the optical component. The CTEs of the mount and mirror material are matched as good as possible (Fused Silica with M93 Invar). The bond between mirror and leaf spring is optimized by TNO developed tools and material models.[1]

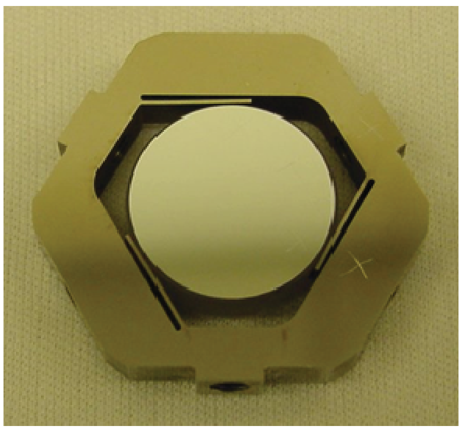

Fig. 6. Breadboard of a mirror bonded to three tangential leaf springs as used in the GAIA Wave Front Sensor mount design.

4) Verification by test

Breadboard testing is performed on this and other mount designs, the low WFE in combination with the high stability were the base to select this mount design for the flight models. The test sequence is: WFE measurement at 130 K, vibration tests, thermal cycling. Before and after all test steps the WFE and angular stabilities were measured by a Zygo interferometer.

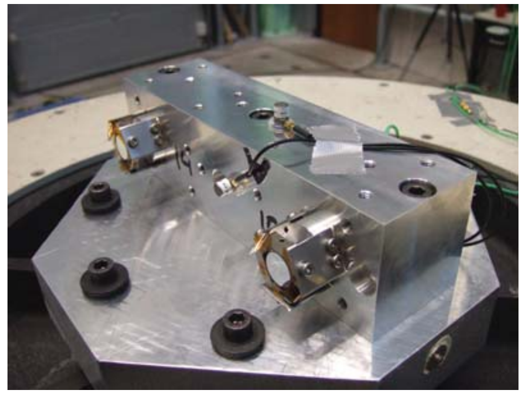

Fig. 7. Two breadboards of the mirror mount on the shaker. To avoid misalignment due to the mounting on the shaker interface and to keep the reference plane on the mount flat enough for a reference measurement the mounts are iso statically mounted on the shaker.

Before and after all test steps the WFE and the angular stability were measured by a Zygo interferometer. In the table below the relative tilts between the mount and mirror before and after the vibration testing is shown. The maximum measured instability in pointing is 4 microradian for sample 1 around the X axis.

Relative component tilt with respect to mount reference (µrad)before, after and during the vibration tests.						
Sample #	Rx before vibration tests	Ry before vibration tests	Rx after vibration tests at 17.3 g RMS	Ry after vibration tests at 17.3 g RMS	Rx after vibration tests at 30.2 g RMS	Ry after vibration tests at 30.2 g RMS
1	22	87	24	84	26	84
2	1	9	1	12	3	11

Table 2. Tilt stabilities and before after and during the vibration test with levels up to 30.2 g RMS. All measured values well within the required values.

Relative angular stability measurements between the mount and component are performed between ambient temperature and the operational temperature at 130 K. The table below shows the measured stabilities and WFE's. The worst case instability measured is 9 micro radians and the maximum WFE measured is 24 nm PV.

Relative component tilt with respect to mount reference (milli radians) and WFE for Ambient to 130 K and vice versa.					
Sam ple #	Measured RX Ambient to Cryo [mrad]	Measured RY Ambient to Cryo [mrad]	Measured RX Cryo to Ambient [mrad]	Measured RY Cryo to Ambient [mrad]	WFE Peak to Valley [nm]
1	0.007	0.004	0.007	0.008	19
2	0.004	0.002	0.001	0.007	22
3	0.001	0.008	0.001	0.010	24

Table 3. Tilt stabilities and WFE's measured from ambient to 130 K and vice versa. All measured values are well within the required values.

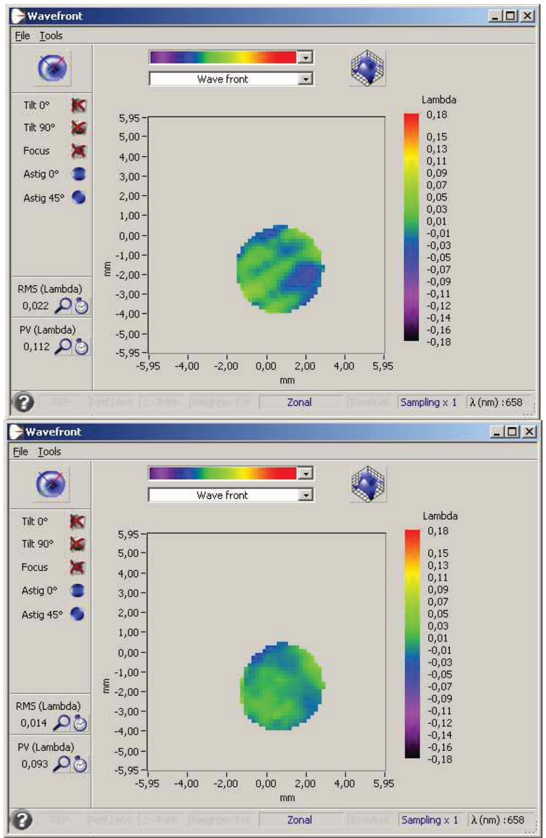

Fig. 8. Top; the WFE of sample 3 at ambient temperature and pressure. Bottom; the WFE of sample 3at 130 K and vacuum conditions. Peak to Valley difference < 12 nm.

After the breadboard testing the flight models were successfully build, tested and delivered to Astrium Toulouse.

C. LISA PAAM mirror mount

1) Introduction

Detection and observation of gravitational waves requires extremely accurate displacement measurement in the frequency range from 0.03 mHz to 1 Hz. The Laser Interferometer Space Antenna (LISA) or NGO (New Gravitational wave Observatory (NGO) missions will attain this by creating a giant interferometer in space, based on free floating proof masses in three spacecraft's. for details see [13,14]

Due to orbit evolution and time delay in the interferometer arms, the direction of transmitted light changes. To solve this problem, a pedometer stable Point-Ahead Angle Mechanism (PAAM) was designed, realized and successfully tested. The PAAM concept is based on a rotatable mirror. The critical requirements are the contribution to the optical path length (less than 1.4 pm/√Hz) and the angular jitter (less than 8 nrad/√Hz). As a part of the mechanism the mirror mount has to be stable up to picometer level over time scale of hours. For this mount a bonded axial leaf spring design is implemented. Interferometric measurements with a triangular resonant cavity in vacuum proved that the PAAM and thereby the bonded radial leaf spring mount meets the requirements. For details on the PAAM see [4].

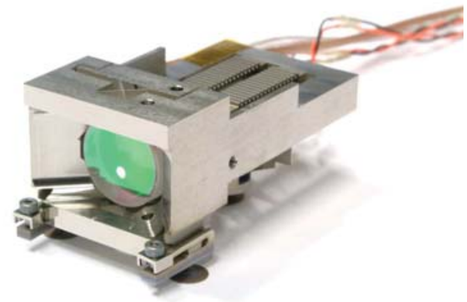

Fig. 9. The PAA Mechanism; the mirror is mounted with 3 axial place leaf springs; the leaf springs are bonded to the mirror. The axial leaf springs are difficult to see in this photo, see for the concept figure 4 (t) of this paper.

2) Requirements

The design driving requirements for the mount are:

- Mirror piston stability of <0.7 pm/√Hz in the LISA measurement band (0.03 mHz to 1 Hz)
- Tip/tilt stability (RX,RY) of the mirror with respect to the structure better than 4 micro radian over life time. This includes after launch loads up to 25 g RMS and thermal cycling in the range of -60 °C to +80 °C.

3) Mount design

The mirror is mounted iso statically by three axial leaf springs. The thermal center is located in the center of the reflective surface of the mirror. The CTE difference between the structure material and mirror material is decoupled by the leaf springs. The component is bonded to the leaf springs. See for the concept of the mount design figure 4 (left) of this paper.

4) Verification by test

The complete mechanism is tested by the Albert Einstein institute in Hannover Germany. A dedicated test setup is developed in scope of the LISA mission. In the figure below the Optical Path Difference measured by the Albert Einstein Institute is shown [11]. The piston stability of the mechanism including the bonded axial mirror mount is half of the shown values.

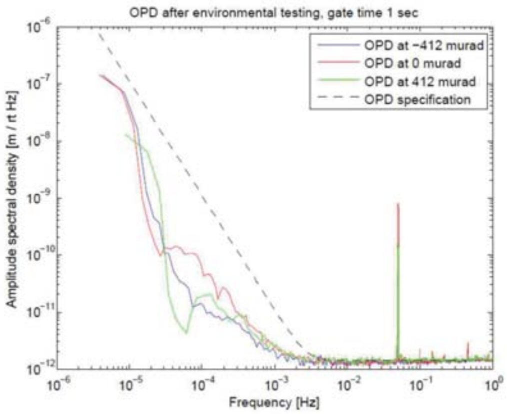

Fig. 10. Amplitude Spectral Density of the OPD measurements, the piston stability of the mirror mount is a part of the measured value. Measured values are expected to be dominated by the noise in the measurement setup. The peak at 50 mHz is introduced for alignment in the cavity and is caused by the rotation of the mechanism.

From the measurement results it can be concluded that with a proper design a bonded iso static mount can be stable over times scales of hours up to the picometer level. Instabilities introduced by the adhesive can be minimized by proper design and dimensioning of the mount.

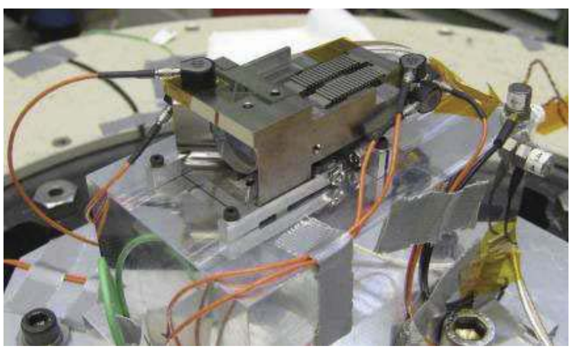

Fig. 11. The mechanism on the vibration facility. Tilt stabilities before and after vibration test (25 g RMS) have been measured to be well below 4 micro radian.

At the moment the mechanism is ready to be integrated on the LISA Optical Bench EBB. For details see [10]

IV. Conclusions

TNO has built up a lot of experience with the bonded iso static mounting concept by implementing it in several different applications . Thanks to extensive verification campaigns very good knowledge of this mounting concept with respect to strength, stability and wave front errors is built up. This knowledge is developed together with refined material models which are implemented in by TNO developed design tools. With these design tools in combination with extensive test experience, TNO is able to predict the performance of mounting concepts in the preliminary design phase.

This is accompanied by further developing the infrastructure for environmental testing and experimental validation of stabilities and WFE's which is available at TNO. Through the years a more or less standard way of testing has been developed. This has led to a relative inexpensive way to validate stabilities during and after extreme environmental loads. For recent developments in the testing infrastructure at TNO see [12].

The extensive experience with bonded iso static mounts in combination with the in house developed design tools and the experimental validation infrastructure give us the possibility to develop extreme stable mounts at low costs and risks in a short time frame.

V. Acknowledgments

The TROMOMI mount is developed under contract of NSO and ESA in the frame of the ESA GMES Space Component Program. GAIA WFS is developed under contract of Astrium Toulouse and the LISA PAAM is developed under contract of ESA.

VI. References

[1] De Vreugd, J., "Modeling of viscoelastic properties of adhesives," Proc. SPIE 8450 (2012).
[2] De Vries, J., e.a., "TROPOMI, the Netherlands originated atmospheric trace gas instrument in the line of SCIAMACHY and OMI," 62nd International Astronautical Congress, (2011)
[3] Daly, J., e.a., "Structural adhesives for bonding optics to metals: a study of opto-mechanical stability," Proc. SPIE 4444, (2001).
[4] Pijnenburg, J. e.a., "Extremely stable piezo mechanisms for the New Gravitational wave Observatory", Proc. SPIE 8450 (2012).
[5] Kihm, H., e.a., "Lens mount with ring-flexures for athermalization,", Proc. SPIE 8125, (2011).
[6] Mammini, P., e.a., "Sensitivity evaluation of mounting optics using elastomer and bipod flexures," Proc. SPIE 5176, (2003).
[7] Herbert, J., "Techniques for deriving optimal bondlines for athermal bonded mounts," Proc. SPIE 6288, (2006).
[8] Doyle, K., e.a., "Athermal design of nearly incompressible bonds," Proc. SPIE 4771, (2002).
[9] Vosteen, A., e.a., "Wave front sensor for the GAIA mission," ICSO 2010.
[10] d'Arcio, L., e.a., "An Elegant Breadboard of the Optical Bench for LISA/NGO" LISA Symposium 2012, Paris.
[11] Pijnenburg, J., Rijnveld, N., Sheard, B., "Picometer stable scan mechanism for gravitational wave detection in space: LISA PAAM" *38th COSPAR Scientific Assembly*, volume 38, pages 3758--+, 2010.
[12] Verlaan,A., e.a., "A Telescope Assembly Optical Stability Characterization for ESA", Proc. SPIE 8450, (2012)
[13] Weise, D., e.a., "An Elegant Breadboard of the Optical Bench for LISA/NGO", ICSO 2012 Conference Proceedings.
[14] Danzmann, K., "LISA Mission Overview", Advances in Space Research Vol. 25, Issue 6, 2000, 1129 – 1136