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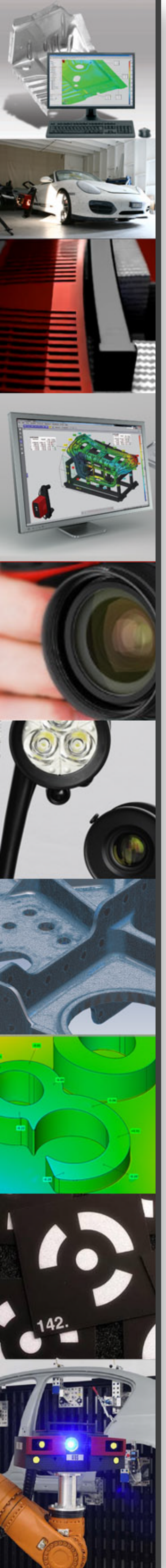

Application Example: Quality Control

Aerospace: Development of a Dimensionally Stable Lightweight Structure for the LISA Pathfinder Science Module

Measuring Systems: TRITOP
Keywords: thermo-elastic, climatic chamber, structure deformation

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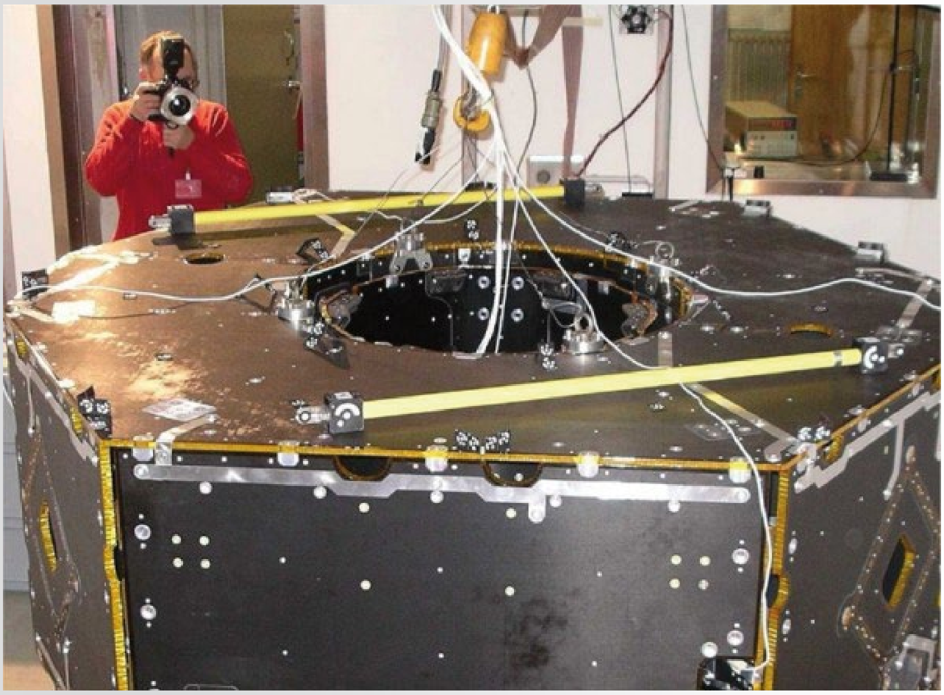

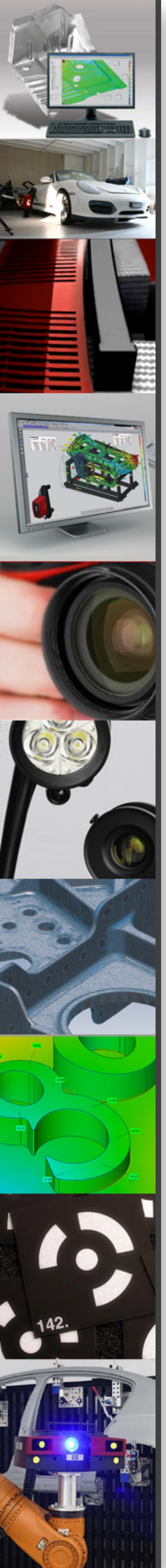

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Quality Control / Aerospace

Development of a Dimensionally Stable Lightweight Structure for the LISA Pathfinder Science Module

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Extract of a paper presented at CEAS 2007 from HP. Gröbelbauer, M. Heer from Oerlikon Space AG, Schaffhauserstrasse 580, CH-8052 Zürich, Switzerland

Overview

The Science Module Structure of LISA Pathfinder – the precursor for ESA's ambitious LISA mission to detect gravitational waves - is designed to fulfil extremely stringent thermo-elastic distortion requirements. It provides the stable reference frame required for the successful operation of both the high precision laser interferometer and the drag-free electric micro-propulsion system. In addition to dimensional stability, the Science Module (SCM) structure offers high stiffness and strength with a reduced mass. The complete structure is manufactured using co-cured CFRP skinned aluminium honeycomb sandwich panels connected to each other by filament wound CFRP cleats. The emphasis of this abstract is the accurate measurement of the thermo-elastic performance in a dedicated distortion test. The assembled structure is placed in a climatic chamber and subjected to temperature variations. Structure deformations are measured by a combination of laser metrology for the inner compartment accommodating the LISA Technology Package and by videogrammetry to determine the distorted shape of the external structure. Recorded deflections are finally compared with the analytical predictions obtained from a detailed 3D structure FEM.

1. Science Module Structure Design

The Science Module (SCM) structure was developed and built by Oerlikon Space AG for Astrium Ltd. and European Space Agency (ESA). It is an eight sided prism with an overall height of ~850 mm and an overall diameter of ~1800 mm built around a central cylinder of ~820 mm diameter (see Fig 1).

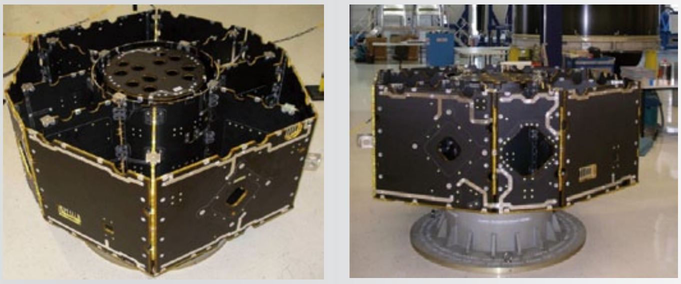
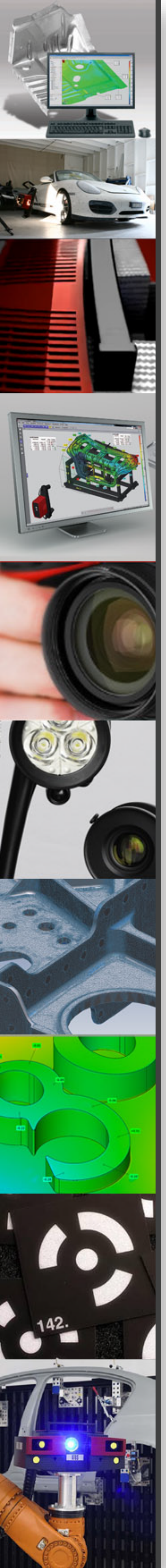


Fig 1: SCM Structure (upper closure panels removed)

2. Thermo-Elastic Stability Requirements

The thermo-elastic behaviour had to be demonstrated with a distortion test where the assembled structure had to be exposed to a uniform temperature variation from +10°C to +40°C.



3. Material Characterisation

The LISA Pathfinder mission requires a dimensionally stable science module structure and a precise knowledge of the thermo-elastic behaviour in order to allow accurate predictions of the gravitational field and its variation. The material characterisation programme commenced with coupon tests covering the quasi-isotropic laminate used for the panel skins and the two main sandwich types used in the structure design.

4. Full Scale Thermal Distortion Test

After extended coupon tests, sandwich pannels were built and tested. The components were tested and then, for the final verification of the dimensional stability a thermal distortion test was needed. The measurements were performed with the fully assembled LISA PF SCM structure in the climatic chamber of METAS in Bern, at temperatures which varied between +10°C and +40°C. In order to generate well defined mechanical boundary conditions, the structure was kinematically supported on the bottom face of the LCA baseplate.

During the full scale distortion test two different measurement methods were applied:

- laserinterferometric measurements, as used for the measurements on component level
- digital photogrammetry (videogrammetry) which was adopted as a complementary measurement method to determine the global distortion of the external structure.

4.1. Laserinterferometric Measurements

The laser interferometric measurement method discussed before and used for the characterisation of individual panels was successfully applied to the assembled structure. The distortions of the LCA support structure and of the primary structure were measured. Numerous cut-outs were implemented into the structure to obtain an unobstructed line-of-sight for the laser beam.

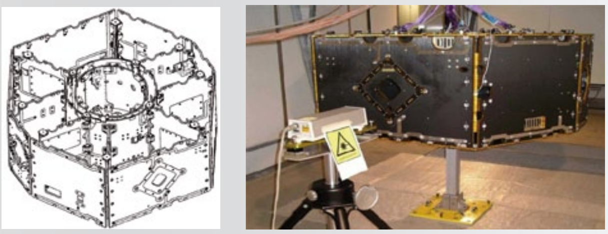
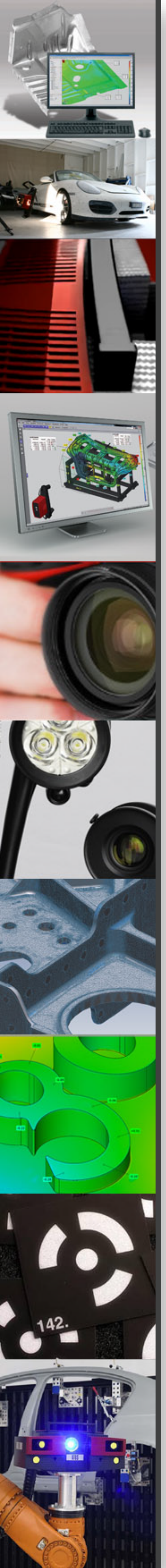


Fig 2: Illustration of different courses of the laser beam with the actual setup, with the self-adhesive optical targets attached to the modul

The laser had to be repositioned and adjusted for every measurement. During the test campaign a total of sixteen temperature cycles have been performed. The measurement data capture the change in distance between measurement and reference mirrors.

The LCA baseplate expands by approximately 11 μm when exposed to a uniform temperature increase of 30°C. The expansion of the primary structure is approximately 100 μm measured along the parallel shear walls and 140 μm along the radial shear walls as shown in Fig 2. Since the mirrors were mounted with a certain distance from the edge of the structure, the real edge-to-edge expansion is about 15% higher than the above measured values.



Although laser metrology is considered to be the most accurate method to measure distortions of one micrometer or smaller, it is not a practical method to determine the distorted shape of a complete structure as only the change of one dimension with temperature can be measured. In addition, the method requires mounting provisions for the interferometer and mirrors and even mass compensation devices when the optical elements are to be fixed on vertical panels.

4.2. Videogrammetry

A well proven method to measure 3D geometry and distortions is by digital photogrammetry, also known as videogrammetry. Videogrammetry is a measurement technology based on optical triangulation in which the three-dimensional coordinates of points (targets) on an object are determined by measurements made in two or more images taken from different angles. These can be obtained from successive images captured by the same camera with a view of the object.

The videogrammetry measurements on the assembled LISA PF SCM structure were performed by the company GOM International using a Nikon D2X 12MPixel digital camera and their data processing software TRITOP. The external structure was equipped with a large number of self-adhesive optical targets. Calibrated reference scales (yellow bars in Fig 3) were positioned close to the test article to provide absolute dimensions.

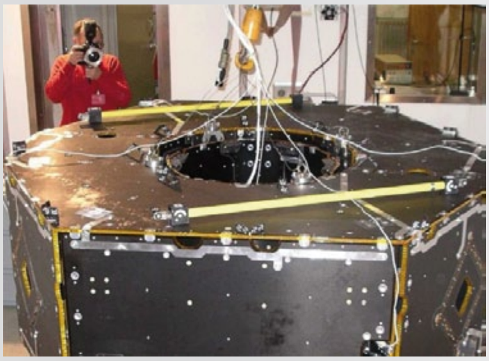


Fig 3: Videogrammetry measurement

It is evident that videogrammetry requires full visibility of the test article and that best results are achieved when the targets are seen from many different angles. To obtain the best possible coverage, approximately 250 pictures were taken at +10°C and at +40°C (see Fig 4).

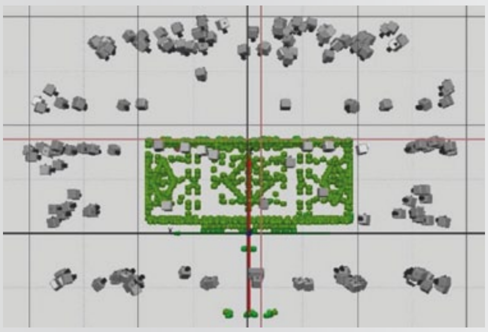
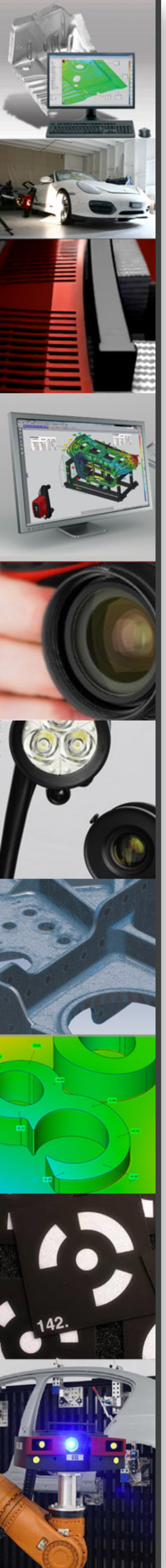


Fig 4: Overview of the camera positions used to generate the images of the test article



The accuracy of the videogrammetry is typically 10-15 µm for objects of the size of the LISA PF SCM structure. Although the accuracy of the videogrammetry is at least on order of magnitude less than the accuracy of the laser metrology, it still provides useful information on the global behaviour. The distortion of the external structure caused by a uniform temperature increase of approximately 30°C is illustrated in Fig 5.

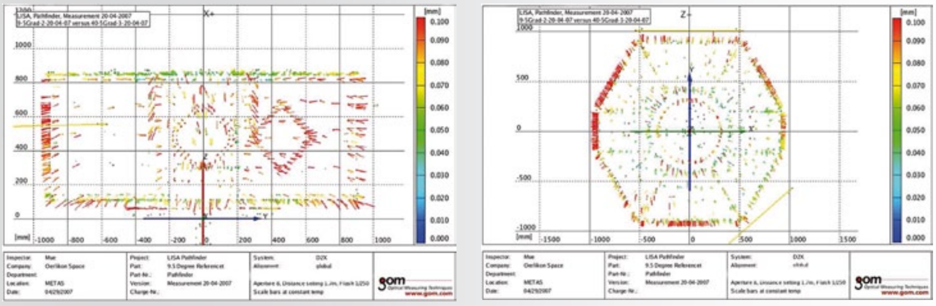
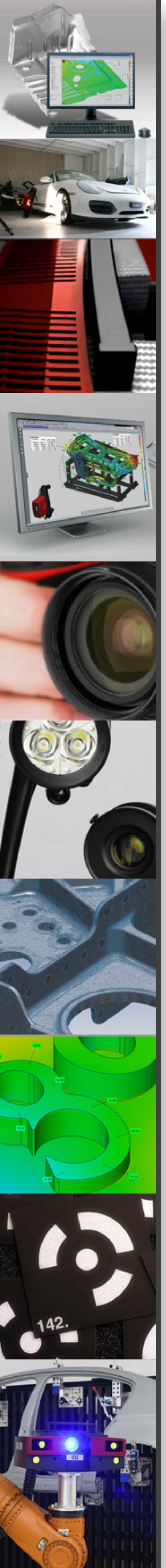


Fig 5: Displacement of targets mounted on external structure for a temperature variation from +9.5°C (reference temperature) to +40.5°C

The structure expands homogeneously and the maximum displacements which were measured on the outer surface of the external structure are in the order of 100 µm. A cross check was performed to confirm that the videogrammetry data is consistent with the results obtained by laser metrology. For this purpose the expansion of the primary structure measured with the laser interferometer was compared with the expansion of the external structure measured by videogrammetry taking into account the transverse (through the thickness) expansion of the external panels and the contribution from the cleated joints between shear walls and external panels.

5. Mathematical Model Correlation

The comprehensive material characterisation programme discussed in section 3 as well as the full scale thermal distortion test contributed to the understanding of the thermo-elastic behaviour of the LISA PF SCM structure. The second objective of the test programme besides the measurement of the distortions was to generate sufficient data to allow the correlation of the finite element model. Since the precise knowledge of the mass distribution is of utmost importance for the success of the LISA Pathfinder mission, the mathematical model of the SCM structure has been built with a degree of detail which is far above the usual FEM standard for satellite structures [3]. The sandwich panel core was modelled with 3D solid elements to account for transverse expansion effects. The behaviour of the complex panel-to-panel connections has been assessed with detailed local FE models involving solid meshed cleats and contact elements. To limit the degrees of freedom in the overall structure FEM, the cleats were finally represented with shell and beam elements with properties reflecting the correct behaviour.



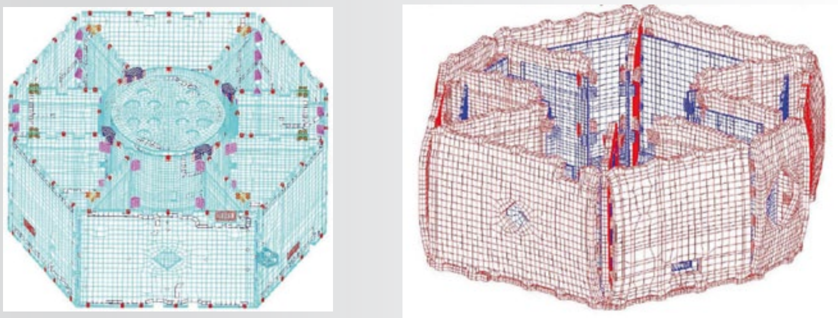


Fig 6: LISA PF SCM structure finite element model with the predicted deformation by finite element calculation for ΔT=30°C

Results obtained from coupon and component tests were used for the material property definition in the finite element model. A uniform temperature increase of ΔT=30°C has been applied to the structure FEM and the calcuated distortions were compared with the results from the full size distortion test. A qualitive illustration of the expanded structure is shown in Fig 6. Besides the global expansion, the thickness increase of the sandwich panels and the local effects of individual metallic edge inserts are also well represented. As the structure is not fully symmetric, the expansion of the parallel shear walls is smaller than the expansion of the longer radial shear walls.

The analytical prediction correlates well with the measurement in both radial and axial directions. Largest deviations are found for the axial displacements at the upper panel edges. The thermo-elastic behaviour of the LCA support structure was correlated in a similar way based on the laser measurements.

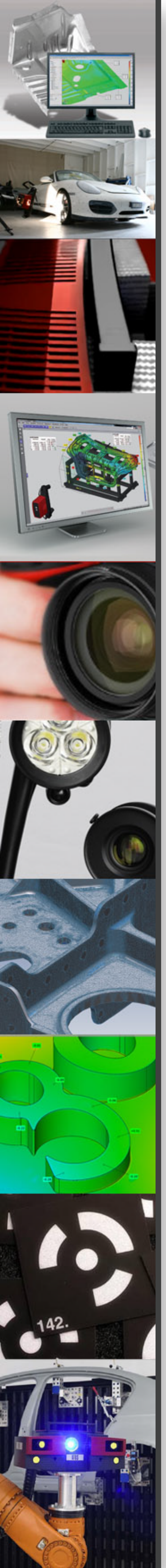
The axial distortion is dominated by the transverse expansion of the aluminium honeycomb core of the LCA baseplate. For an uniform temperature increase of ΔT =30°C the maximum distortion of the LCA support structure is 156 μm in axial direction and 27.2 μm in radial direction.

6. Discussion

The selected approach to develop a dimensionally stable structure for the LISA Pathfinder Science Module and to verify its thermo-elastic performance has been successfully demonstrated.

A full-scale distortion test was considered necessary to demonstrate the performance of the assembled structure and to finally correlate the mathematical model. Instead of applying a complex temperature distribution obtained from the mission thermal analysis, the structure was subjected to a uniform temperature change of 30°C. The advantage of this simple thermal test case is that it could be conducted easily in a climatic chamber and showed good repeatability. The kinematic support concept which provided a stable stand but still allowed the structure to expand freely under thermal loads turned out to be very practical. A test with the structure being freely suspended from slings was attempted but led to laser alignment problems due to small movements of the structure caused by circulating air.

The accurate measurement of small distortions requires measurement equipment with exhibits very low thermal drift. The selected differential plane interferometer proved to be suitable to measure the displacements within the LCA support structure with an accuracy of better than ±0.5 μm. Supplementary videogrammetry measurements helped in the understanding of the global deformation of the structure.



Although the development of a dimensionally stable sandwich structure appears to be straight forward, the experience gained from the LISA PF SCM structure showed that the influence of all materials and components involved in the design must be carefully assessed. The inplane CTE of blank sandwich panels can be doubled depending on the number of inserts installed and the quantity of adhesive and potting compound used. The sandwich panels developed for the LISA PF SCM structure use an aluminium honeycomb core which drives the panel expansion in the transverse direction and must be accounted for in the analysis.

7. Conclusion

Traditional CFRP skinned aluminium honeycomb sandwich panels are still a good choice for the design of stiff and dimensionally stable lightweight structures. In particular for large structures, the CFRP sandwich offers considerable advantages over design solutions based on glass ceramic or ceramic matrix composite materials. However, accurate predictions of the thermo-elastic behaviour are only possible if the analytical models take into account the properties of the complete sandwich panels. The effect of inserts, adhesive and potting compound is significant and can not be ignored. Attention must be paid as well to connection elements such as cleats and fasteners as they contribute to the structural distortion. For platforms requiring high stability, it is beneficial to increase the thickness of the panel skins, to use lightweight core and to reduce the amount of adhesive as far as practical. Coefficients of thermal expansion below 1 ppm/K are feasible and have been achieved for the instrument support structure of the LISA Pathfinder Science Module. In-plane CTE values between 1.5 and 2.5 ppm/K were measured for typical equipment support panels and closure panels. Special filament wound CFRP cleats and brackets were developed to minimise the distortion of the assembled structure. The structure developed and built for the LISA PF Science Module combines excellent dimensional stability, high strength and stiffness at reduced mass and may serve as a valuable example for future developments in the field of stable lightweight structures.

We thank Mr Gröbelbauer and Mr Heer from Oerlikon Space for their trust in our TRITOP measuring system and for this extract of their paper.