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Numerical and Experimental Investigations on an Ultrastable Wavefront Sensor Support Structure

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Abstract

In this paper we will cover the investigations efforts carried out in order to meet stability requirements of a Wave Front Sensor support structure, to be installed and used in the "Métrologie" Beamline of SOLEIL. The active components (gratings, lens and camera) should not have more than 10nm motion relative to each other. Hence, the design objective can be very simply stated: provide a support structure that allows alignment of active components, but also the possibility of maintaining position and allowing reproducibility of measurements within aforementioned limits over periods of months or years. So, the design objective is to obtain a rigid body, both from vibrational and thermal elastic point of view. The additional difficulty here is that the entire setup has to be easily removable, placing stringent limits on total weight and volume, while still ensuring overall reproducibility.

An invar support structure has been designed and constructed, then tested in the Métrologie Beamline hard X-rays hutch. Investigations efforts covered both dynamic and thermal elastic aspects, putting the emphasis on a step-by-step comparison of analysis and testing results. This allowed to double check the major assumptions, and confirm the absence of discrepancies between expected and actual results. Efforts to quantify significant sources of uncertainties where made, covering numerical and experimental approaches. The external disturbances being random, a frequency domain approach is applied, and the final reliability of the structure is found to be acceptable without any specific insulation measure. This seemingly counter-intuitive conclusion exemplifies the usefulness of relying on a consistent set of design rules and effective analysis tools.

Keywords:
Thermal Modal Analysis. Structural Modal Analysis. Experimental Modal Analysis. Thermal Design.Thermal Control. Shack-Hartmann Wavefront Sensor.

1. Motivation and anticipated difficulties

Located at the French National Synchrotron Radiation Source (SOLEIL) , the Métrologie beamline is dedicated to the characterization of optical components. For 3rd and 4th generation sources, optics are limiting factors to the conditioning of X-ray beams*.* At high energy and small grazing angles, optical path errors are in the order of picometers, and optical surfaces quality can only be assessed base on the well known Shack-Hartmann principle: wavefront reconstruction based on a 2D grating, a YAG scintillator and a CCD camera, each interference spot motion being proportional to the local wavefront error.

Since this setup will be used as a calibration system, it will only be put in place at intervals of months or years. This places a number of conflicting requirements on the design, since the setup must be immune against external disturbances and simultaneously sufficiently lightweight.

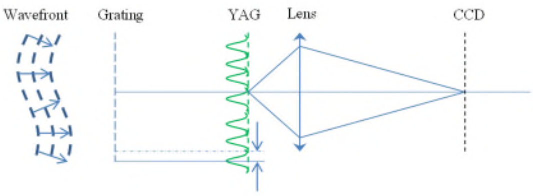

Figure 1. Optical scheme

Additionnaly, it is not practical to directly measure displacements with amplitude of a few nanometers, hence validation of the setup can only be made using an indirect approach, using combined experimental and numerical investigations.

2. Design Methodology / Goals

The design approach was based on simple reasoning. The main idea was to begin with a mechanical setup that was as compact as allowed by the optical demands.

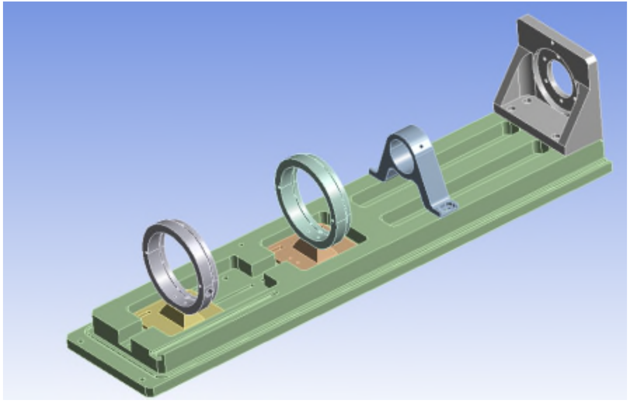

Figure 2. Mechanical support beam and frames - CAD

Further considerations were to reduce thermal mechanical and vibration distortions below allowable, as follows:

i/ Mechanically, the support beam was to be stiff enough so as to provide a rigid base for mounting optical components. Additionally, it had to be connected to its underlying baseplate using compliant supports. This ensured that static deformations were not transmitted to the beam. This also acts as a resilient support to filter ground transmitted vibrations. Assuming the acceleration at base is known, and the response is dominated by the first elastic mode, an order of magnitude of the beam distorsion can be estimated following the approximate relationship: $d \sim \frac{\gamma_{base}}{4\pi^2 {f_{elastic}}^2}$

Assuming an acceleration amplitude at base of 10 mm/s², the first natural frequency should be largely in excess of 160 Hz.

ii/ Regarding thermally induced distorsions, a low CTE material was selected (Invar, CTE~2 ppm/K) The bending radius, angular devation and the total out-of-plane distorsion of the beam obeys the well-known relationships:

$$R_c = \frac{thickness}{CTE \times (T_{top} - T_{bot})}, \theta_{max} = CTE \times \frac{L}{2} \times \frac{(T_{top} - T_{bot})}{thickness}$$

And:

$$d = CTE \times \frac{L^2}{8} \times \frac{(T_{top} - T_{bot})}{thickness}$$

Beam thickness is 30 mm and total length about 0.5 m. Based on the previous relationship, the allowable temperature difference between top and bottom faces of the support beam should not exceed 2 mK. This is 500 times less than the (P-V) expected ambient temperature deviation in the hutch.

3. Analysis Methodology

The analysis approach consisted in using a variety of estimations, with increasing fidelity:

Vibrations:
i/ estimate first bending natural frequency, using hand calc's
ii/ compare with Finite Elements (FE),
iii/ confirm with Experimental Modal Analysis
iv/ inject base motion spectrum into FEM and solve for response amplitudes

Thermal-mechanical:
i/ estimate first thermal time constant, using hand calc's
ii/ compare with FE
iii/ confirm with Experimental Thermal Transfer Function
iv/ estimate thermal-structural response using hand calc's
iv/ inject temperature transients into FEM and confirm

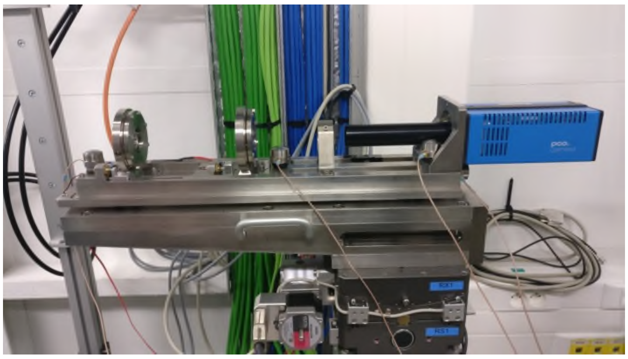

Figure 3. Actual setup (cover removed)

4. Analysis Results

4.1. Vibration Response

Assuming the beam is in free-free conditions, and its mass is uniformly distributed, an estimation can be made, and compared against FE and experimentally derived values (EMA).

Table 1 : First bending mode frequency [Hz]

Hand calc's	Finite Elements (ANSYS)	Measurements(EMA)
270	239	192 (+/- 1)

Secondly, the frequency response to a unitary acceleration applied in every axis, and multiplied by the measured acceleration spectrum at base, to yield probablisitic estimates :

Table 2 : 95% probability of non exceedance levels [nm RMS]

Longitudinal	Transverse	Vertical	Combined
0.15	0.05	0.40	0.43

4.2. Thermal Mechanical Response

Assuming natural convection (h=10 W/m²/K), the Thermal Time Constant of the beam was predicted first analytically and then using ANSYS MathAPDL capabilities [3].

Table 3 : First thermal mode Thermal Time Constant [s]

Hand calc's	Finite Elements (ANSYS)	Measurements
8775	7098	8640 (+/- 600)

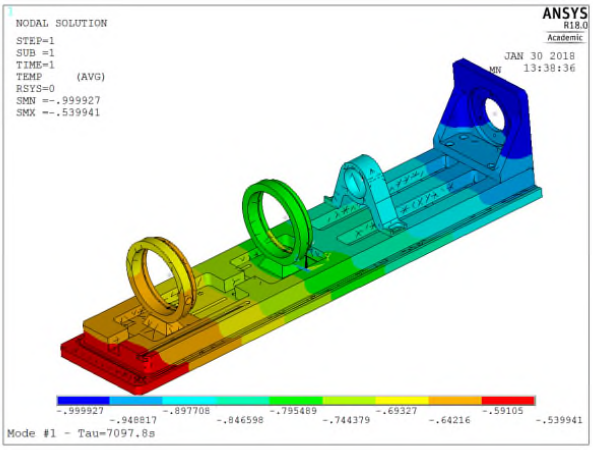

Figure 5. First Thermal mode (normalized to unity)

Based on the PSD of temperature transient recorded in the hutch, and assuming that the beam behaves like an ideal low-pass thermal filter with f_{cutoff} =$1/(2\pi \times TTC)$, response variance can be roughly estimated to be 8 mK. Based on relative thermal resistance (conduction/convection), this yields a through thickness temperature difference of 2% of the latter, i.e. 0.16 mK, hence an error position of about 0.8 nm RMS. This can be further compared with FE results, to check for consistency.

Table 4 : 1-sigma response levels (assuming h_{conv}=10 W/m²/K)

Hand calc			FE (ANSYS)		
T_{mid} [mK]	T_{top}-T_{bot} [mK]	d [nm]	T_{mid} [mK]	T_{top}-T_{bot} [mK]	d [nm]
8	0.16	0.8	9.3	0.45	0.7

It can be noted that hand calculations provide estimates that match high-fidelity, FE analysis to within 50%, which helps gaining confidence in the robustness of results.

5. Summary and Conclusion

Based on a series of simple reasoning and estimations, it was shown that a seemingly difficult performance requirement was feasible without resorting to any specific insulation remedial measures. This rather counterintuitive statement relies on a hybrid (experimental/analytical) approach, illustrating :

i/ the efficiency of frequency domain methods, both for thermal-mechanical and vibration induced disturbances,

ii/ the usefulness of being able to carry out evaluations rapidly and confidently at key points during the design process.

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