THERMAL MODEL VALIDATION OF THE CRYOGENIC OPTICAL MIRROR SYSTEMS FOR SIRIUS/LNLS

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ABSTRACT

Sirius is the fourth-generation synchrotron light source that came into operation in 2020 in the Brazilian SynchrotronLight Laboratory (LNLS), providing a photon beam with a much lower emissivity than the previous second-generation light source in Brazil (UVX). One of the challenges of dealing with in such a light source is the high power density that may affect the beamline optical elements by causing figure deformations that deteriorate the quality of the beam. Indeed, surface specifications for height errors of X-ray mirrors are often within a few nanometers, possibly going below 1 nm. To deal with this power management challenges, thermo-mechanical designs based on cryogenic silicon have been developed*, taking advantage of the fact that the coefficient of thermal expansion of the material is nearly zero in temperatures of about 125 K. A liquid nitrogen (LN2) cryostat connected to the optics by copper braids has been used handle moderate power loads**, reducing costs as compared to closed-circuit LN2 cryocoolers and mechanically decoupling flow-induced vibrations from the optics. To guarantee the functionality of such systems, lumped mass thermal models were implemented together with auxiliary finite elements analyses, considering heat transfer by conduction, convection and radiation among multiple bodies. These models were of paramount importance to optimize the systems with limited computational cost, either in defining the geometry of the components. With the first systems in operation, it has been possible to compare and validate the developed models, and to carry out optimizations to improve them for future projects.

LUMPED MASS MODEL

The purpose of this method is to reduce complex systems in mass and thermal resistances. Each resistance is founded by different equation. Look at the alongside example.

The values for the model development are either theoretical or were found from previous ANSYS simulations.

Contact Resistance

It is the thermal resistance measured between contacts [1] and [2].

$$R_{con} = \frac{\Delta T}{Q}$$

Conduction Resistance

It is resistance founded by Fourrier's equation. In this example the equation for 1D is given.

$$R = \frac{\Delta T}{Q} = \frac{\Delta x}{kA}$$

Radiation Resistance

The approach for calculating the thermal radiation resistance was from Gebhard's equation [3] for two bodies.

$$Q = \varepsilon_i A_i B_{ij} \sigma\left(T_i^4 - T_j^4\right)$$

Gebhard's Factor

$$B_{ij} = F_{ij}\varepsilon_j + \Sigma_k F_{ik}(1-\varepsilon_k)B_{kj}$$

$$R_{rad\ i,j} = \frac{\frac{1-\varepsilon_i}{A_i\varepsilon_i} + \frac{1}{A_i F_{i\to j}} + \frac{1-\varepsilon_j}{A_j\varepsilon_j}}{\sigma\left(T_i^2 + T_j^2\right)\left(T_i + T_j\right)}$$

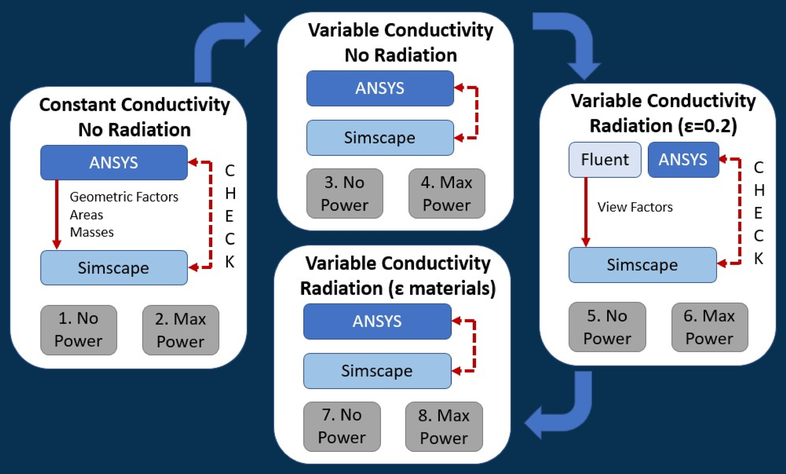
Convection Resistance

This is the resistance is found from Newton's law.
T∞ is the temperature of the hutch (24 °C) or 77 K (temperature of the LN2 cryostat).

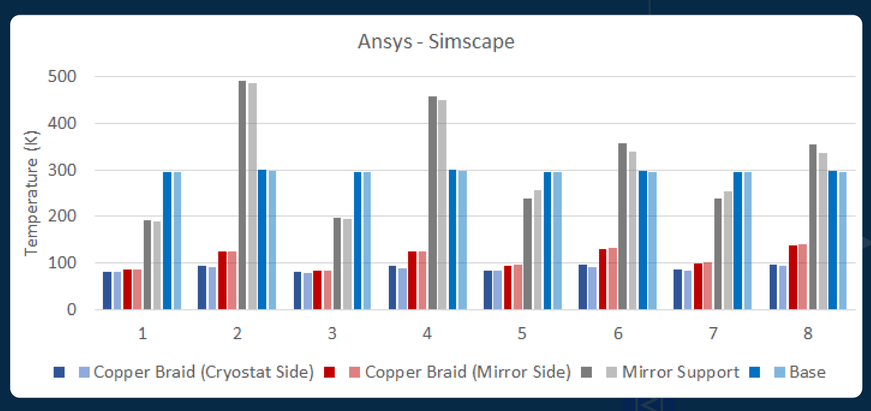
$$R_{Conv} = \frac{(T\infty - Ts)}{Q} = \frac{1}{hA}$$

RESULTS

MODEL DEVELOPMENT



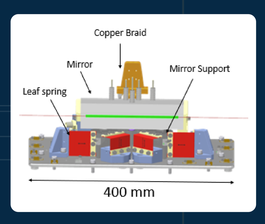
Developmental stages scheme.

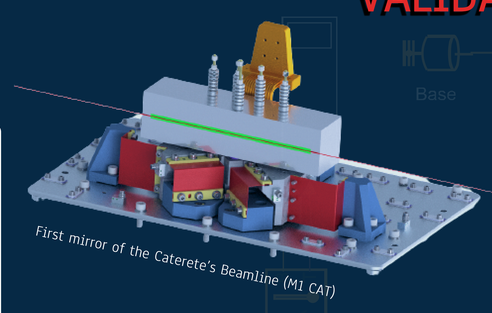


Difference of cases between simulation using FEA (ANSYS - dark) and lumped mass method (Simscape - light). The case are the same of the figure above.

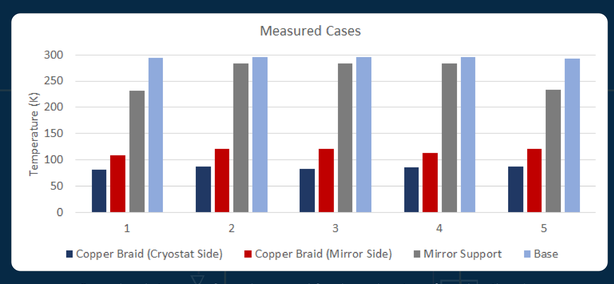
VALIDATION

CAT M1

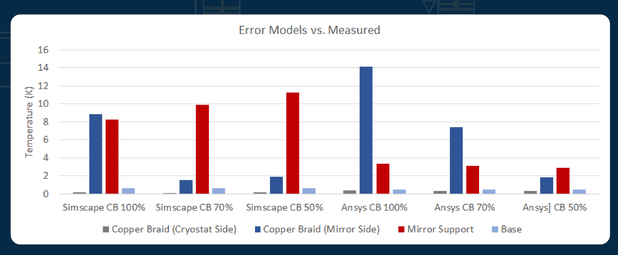




Measured Cases	Power CB Mirror (W)	Power Mirror Suppport (W)
1 - No Power	0.0	0.0
- Controlled (LN2 Low Flow Rate)	1.2	3.3
- Controlled (LN2 High Flow Rate)	2.7	3.4
4 - Mirror Support Controlled	0.0	3.5
5 - CB Mirror Controlled	1.0	0.0

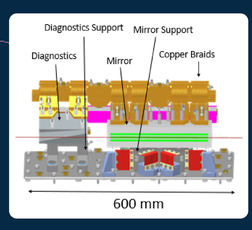


Comparison between the lumped mass model and experiments performed on the mirror.

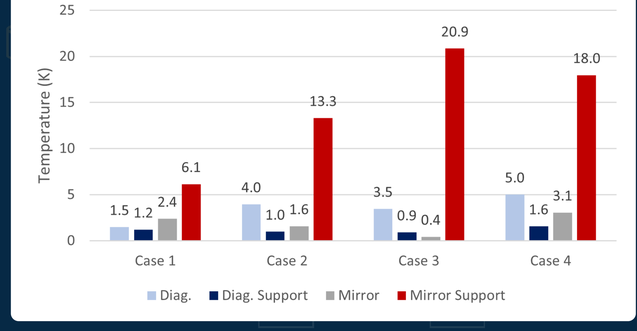


Average of the absolute temperature errors obtained for the five cases presented in Fig. 5 for M1 CAT incomparison with FEA and lumped mass models considering different copper braid efficiencies.

CNB M1



Power (W)	Case 1	Case 2	Case 3	Case 4
Diag.	0	0.4	2.9	17
Diag. Support	0	0.4	6.9	1.1
M1	0	5.2	10.9	35.8
M1 Support	0	1.5	5	3.7



Average of the absolute temperature errors obtained for the four cases presented for M1 CAR incomparison with lumped mass model.

CONCLUSION

The updated lumped mass models have contributed tovalidate and improve thermal modeling of the first mirrorsystems, not only defining power requirements for controlheaters and PID control parameters under variable opera-tional conditions. Also diagnosing system issues, as themanufacturing limitations of the first copper braids. Fur-thermore, a trustful Simscape model makes the dimensionof the parts during the design phase faster than by usingFEA, since it is necessary only changing numbers insteadof redraw pieces.The differences founded between models and measure-ments were below 10 K and in the non critics elements.Apart from refinement of model bodies with high gradients (52 K), we are currently optimizing the nitrogen flux system.

Although the mentioned divergences, this modelling tech-nique proves to be enough to the application, keeping themirror deformation within the requirements and has beenalso used in other mirrors and monochromator projects onSirius.

REFERENCES

[1] SCOTT, S. “Thermal contact between Silicon and Copper”. MEDSI Design Guidelines. Barcelona: [s.n.]. 2016. p. 4.
[2] BERGMAN, T. L. et al. “Fundamentals of Heat and Mass Transfer”. 7. ed. Jefferson: John Wiley Sons, 2012
[3] DSPE, https://www.dspe.nl/knowledge-base/thermomechanics/chapter-2-in-depth/2-4-thermal-radiation/2-4-3-gebhard-method/