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A real-time control system for mirrors local slope errors using thermal actuators: design concept and performance estimation

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Abstract

This paper will describe the effort undertaken in order to investigate the performance of a mirror slope error control system based on thermal actuators. For situations where high accuracy and stability are required, such as demands encountered in next-generation synchrotron radiation beamlines, the quality of the optical surface as manufactured is in the sub micro radian region. This quality can be rapidly degraded by environmental effects such as mounting loads and thermal mechanical effects.
In order to compensate for those inevitable deviations, it is proposed to fit such a mirror with thermal sensors and actuators. While the idea is not new, it has often suffered a lack of confidence in the responsiveness of the system. In this study, we use a systematic approach by estimating the bandwidth of an optimal closed-loop system, using a linear thermal mechanical model. Secondly, an experimental verification of the open-loop thermal response is made, aiming at capturing the delay introduced by non-ideal thermal contact between the mirror substrate and the thermal probes. Lastly, we estimate the performance of the control system by taking into account those non-idealities.

Optical figure errors, thermal actuators, mirrors, thermal-mechanical distortions, real-time error compensation, Pseudo Random Binary Sequence (PRBS), thermal frequency response function

1. Scope and Motivation

At light source facilities working with high energy photons, it is crucial to obtain and maintain small figure errors (well below the microradian level) for the beam conditioning optics. In many situations, although high reflectivity and high thermal conductivity materials - typically silicon- are used, beam deposited loads can be very (hundreds of W/mm²) that large thermal gradients develop, followed by mechanical bending and subsequent defocusing of the reflected beam ([1]). One possible solution is switching from water cooling to cryo (LN2) cooling, resulting in enhanced thermal conductivity and smaller instantaneous coefficient of thermal expansion ([2]). In this paper, we develop a proof of concept of an alternative, more economical option, where the thermal gradients are canceled by providing heat opposite to the photon beam, using a realtime compensator.

Firstly, the thermal mechanical performance of the control system is predicted *ab initio,* assuming perfect contact between the thermal probes and the mirror substrate. Secondly, we build and measure the thermal frequency response of a dummy aluminum mirror. Lastly, we use the measured response to estimate the additional delay due to the thermal sensors reading and update the predicted performance.

2. Initial Performance Estimation

In this section, we briefly describe the steps taken to estimate the expected performance of the system and the results obtained.

2.1. Thermal-mechanical model

To validate the concept, a finite elements thermal mechanical model has been developed. It is made of a rectangular block of silicon (160x60x25), tightly held between copper heat exchanger blocks (Fig.1). Water is circulated in 6mm diameter channels running through these blocks where the mass flow rate is large enough so that the temperature rise can be neglected, and the heat convection coefficient is close to 10 000 W/m²/K. Also, we assume near-perfect thermal contact conductance at the Si/Cu interface, which is a reasonable considering the good flatness, low roughness and high contact pressure that are usually obtained in such systems.

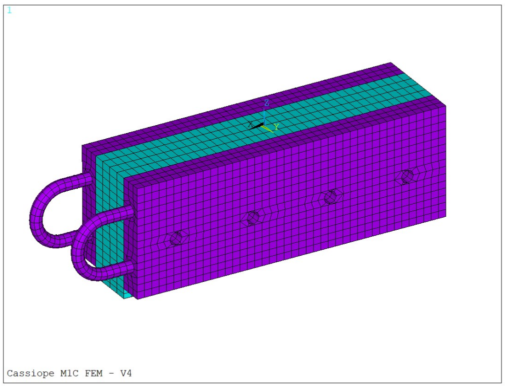

Figure 1. Thermal mechanical FEM of the actual system.

At this stage, we assume that temperature readings are perfect i.e. the temperature probes are linear and induce no additional delay.

2.2. Controller design and results

The thermal FEM has been analyzed using a thermal modal analysis procedure and later on condensed into a state-space representation. All modes with time constants larger than 0.1 s have been included, and a static correction has been used ([3]). For such a situation, the most significant mode, corresponding to heat unbalance between the top and bottom of the mirror, has a time constant of 3 s, which places a lower limit on the system time response.

A simple PI controller has been built for which a varying heat load, *w,* corresponding to the varying beam heat load*,* is applied on the mirror top surface, while a control load (using a foil heater) is applied at the bottom of the mirror (Fig 2).

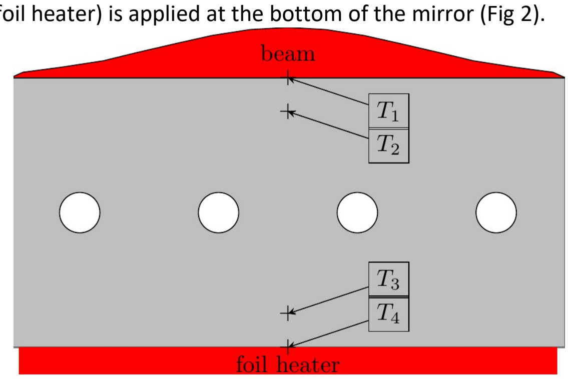

Figure 2. Heat load (beam), proposed sensors positions (T1,T2,T3 and T4) and the control (foil heater) (side view).

Ideally, one would be tempted to place the temperature probes exactly on the top and bottom surface (T_1 and T_4), but this is neither possible, because of radiation induced damage, nor desirable because the heat loads are not uniform and we want to avoid placing the probes in regions of high temperature gradients. Hence, we use probes located 10 mm below and above the top and bottom of the mirror surface (T_2 and T_3). Since we are dealing with a material (silicon) with a thermal diffusivity in the order of 100 mm/s² (at room temperature), this offset should limit the response time to 1s. This will, however, induce a delay in the open loop response of the system and obviously limit its bandwidth. Using this model, the PI controller characteristics are governed by the phase margin. In order to guarantee a phase margin of 60 degrees, coefficients of Kp= 2 and Ti= 10 s are acceptable. Using these figures, the controlled variable (thermal bump) is shown to be reduced by a factor of 50 and the response time is about 15 s (Fig 3).

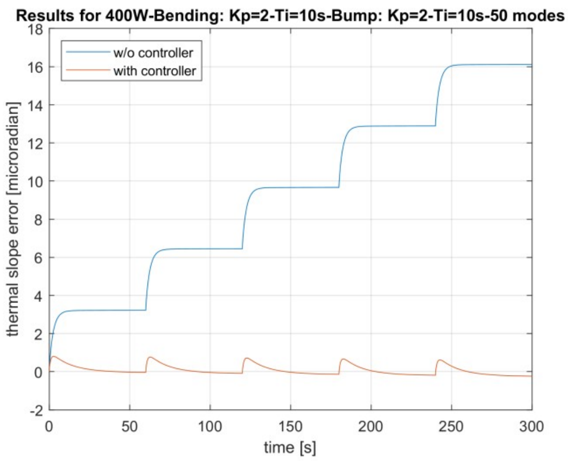

Figure 3. Response to a stepped increase in photon beam power

It is important to note that the residual offset is caused by the inhomogeneity in the temperature field: since the beam load is deposited on a fraction (~10%) of the total mirror width, the temperature read by the upper probe (located on the mirror mid-plane) is an overestimation of the average mirror temperature, hence the controller is slightly overcompensating. This performance is largely acceptable. However, it is entirely dependent on the ability of the model to predict thermal dynamic responses. This is the reason for carrying out experimental frequency response measurements as described below.

3. Experimental validation

3.1. Setup description

An aluminum mirror with dimensions close to that of the actual system (150x60x20mm) has been used for validation of the concept. Aluminum and silicon have almost equal thermal diffusivities, so that using similar dimensions, the thermal frequency responses should be very close to one another. The block has been fitted with commercial heat sinks, and equipped with a heater foil on its lower face. Temperature probes were miniature, commercial thermistors, located in holes filled with thermal conductive paste.

3.2. Numerical Response

The system has been modeled in a simplified manner: notably, the heat sink has not been explicitly modeled but accounted for as an enhanced convection on the mirror lateral sides (h= 40 W/m²/K). This comparatively low convection coefficient makes the measurements of temperature differences much more difficult compared to the final situation, since the temperature gradient along the vertical axis will be comparatively two orders of magnitude smaller. In order to guarantee full accuracy, the thermal Frequency Response Functions (FRFs) have been obtaining by inversion of the full dynamic conductivity matrix following the procedure given in [3].

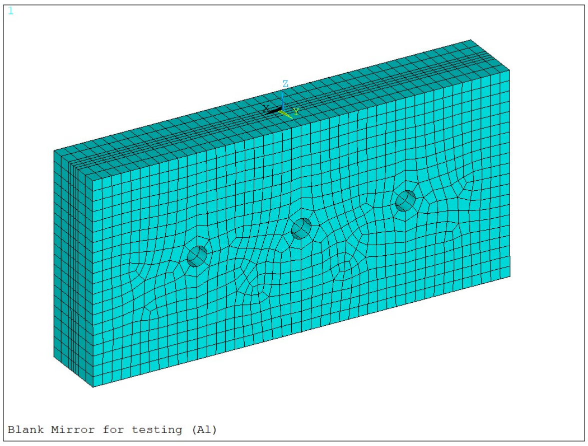

Figure 4. FEM of the test mirror.

The uncertainty induced by the sensor vertical placement in our model has been checked (Fig 5). In our case, sensors are 2.2mm in diameter and their mounting holes are 3mm, so probes are only known to be placed between 4 and 6mm away from the top and bottom of the mirror surfaces. As is shown (Fig. 5), below 10^{-1} Hz, the sensor vertical placement is not critical, i.e. the uncertainty induced is less than 5 degrees.

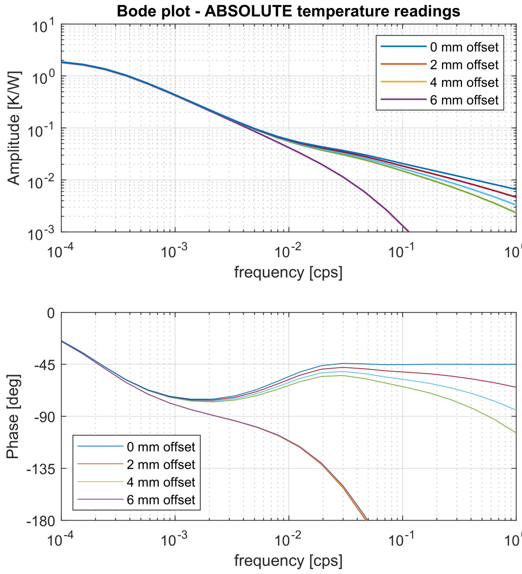

Figure 5. Numerical thermal FRFs - Absolute responses as a function of sensor placement.

Lastly, the relative (i.e. difference between bottom and top sensors) temperature readings are estimated, and plotted in Fig.6. As expected, below 10^{-2} Hz, conduction dominates, so that the temperature response is flat while above 3 10^{-2} Hz, the diffusion effect reduces the transmissibility.

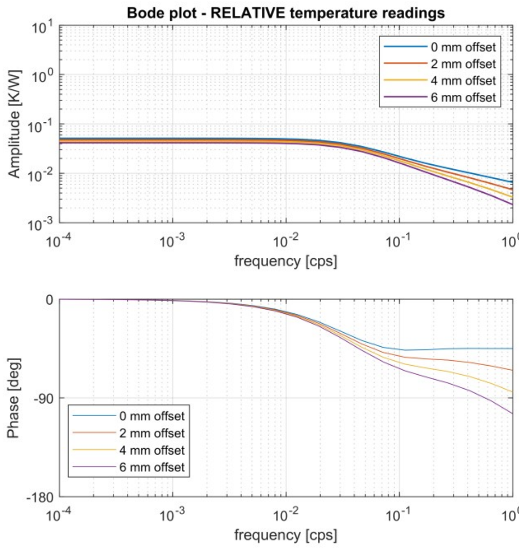

Figure 6. Numerical thermal FRFs - Relative responses as a function of sensor placement.

3.3. Experimental Response

The thermal response has been experimentally characterized using the setup shown below (Figs.7a and 7b). A lightweight setup was built using standard hardware (MAX31865 RTD amplifiers and commercial NTC's). Also, as a powerful cooling system was not available to us for these tests, only moderate thermal power loads could be applied. Lastly, since the principle aim of this study is to capture the additional delay due to the actual contact of the temperature sensors contact with their surroundings, the frequency range of interest is essentially 10^{-2} to 10^{-1}Hz. In this frequency range, the relative response is of the order of a few 10^{-2}K/W, which in turn calls for relatively high resolution, noise-free measurements, ideally at the mK level.

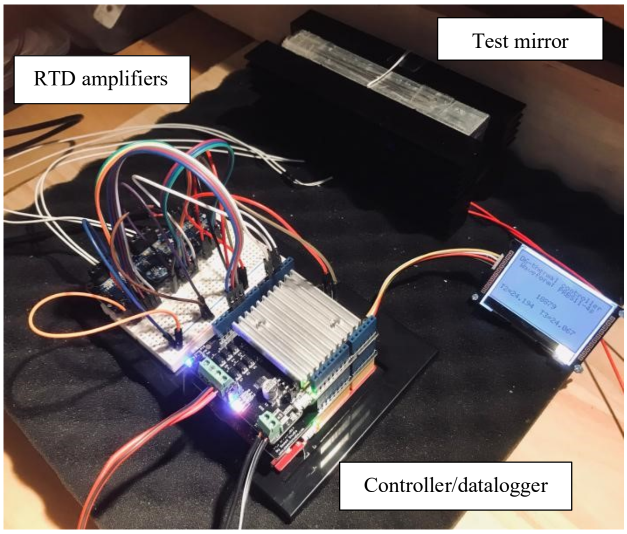

Figure 7a. Experimental setup - overall view

The final tests have been conducted in surroundings where the temperature variation was below 0.1K/day, in the absence of heat source (including human presence). Hence, an autonomous, lower power setup (~0.6Wth) was necessary .

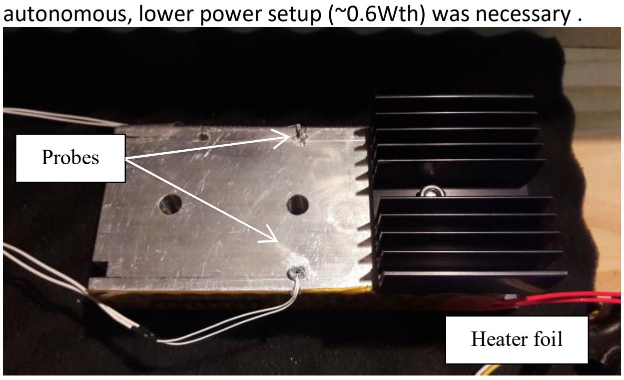

Figure 7b. Test mirror with probes (heat sink partially removed)

Obtaining accurate measurements proved to be a rather challenging task, especially in a non-controlled environment and using temporary circuitry. After careful tuning of the parameters the final results are quite satisfactory. It might be interesting to note that although in principle, any wide band signal could be used for excitation, in practice this is not the case. Troubleshooting of the setup proved rather difficult using traditional (gaussian) random signals, since only mean square coherence can be used as an indicator for the quality of data (Fig 8). Although this is a perfectly rigorous approach, this is of little help for the experimenter since frequency domain data do not produce information easily related to experimental conditions.

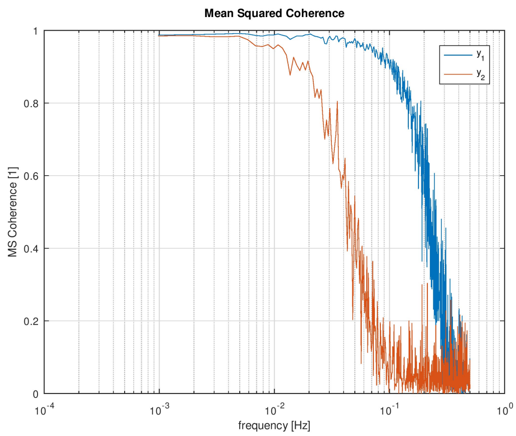

Figure 8. Mean Squared coherence - Input : PRBS Output: temperature.

Switching to Pseudo Random Binary Sequences (PRBS) helped (see [5] for an interesting discussion), in so far as the reproducibility of the test procedure could be quantified, both statistically and in the time domain. It helped detect and discriminate external disturbances, the settling time for the setup, and wiring problems within the electronics.,. Another benefit of using PRBS is that, by varying the order of the sequence, it is possible to adjust the duration of the excitation period, allowing for shorter test times (at the expense of bandwidth lower frequency).

The final results provided here (Fig. 9) have been obtained using an 9th order (repetition period: 511), and a clock time of 2s giving a time period of about 1000s.

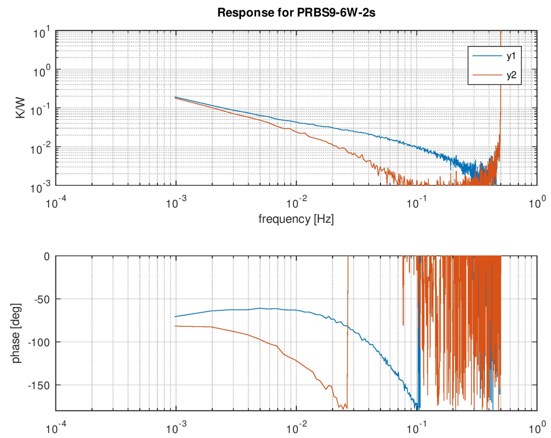

Figure 9. Experimental thermal FRF - Individual responses.

3.4. Estimation of sensors dynamic response

By comparing figures 6 and 9, we get a direct confirmation that the numerical procedure adequately predicted the experimental response, in the low frequency regime. For shorter time periods, as expected, the measured response is much lower and has larger delay compared to its numerical (ideal) counterpart (Fig 10).

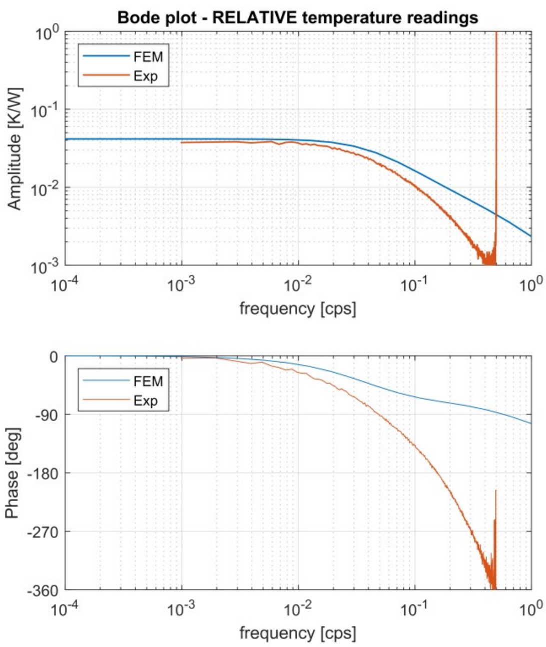

Figure 10. FEM vs experimental thermal frequency responses.

From this comparison, we can extract an experimental model for our sensors, namely, a 1st order system in series with a delay: $H_{probe}(s)=\dfrac{e^{-s\tau_d}}{1+s\tau_f}$ with τ_d =2.5s and τ_f =1.6s.

4. Update of controller performance

After introducing the sensor dynamics into the thermal-mechanical closed loop without modifying the control parameters, it becomes unstable. Therefore, it has been necessary to reduce both the P and I terms by a factor of 2.5. Obviously, the performance is degraded (Fig. 11), but only by a small amount so that our control system remains highly viable.

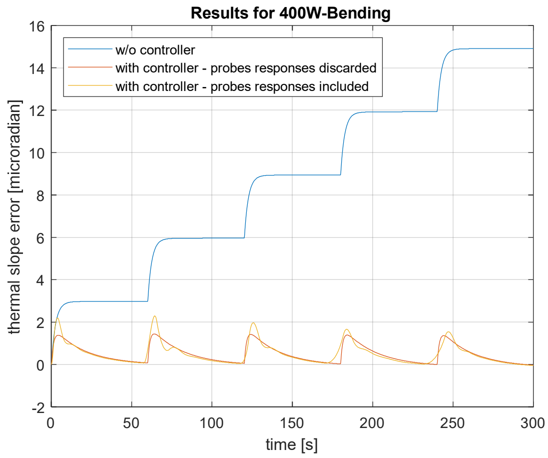

Figure 11. Thermal mechanical controller final performance

5. Summary and conclusion

In summary, we have built a numerical model to estimate the performance of a real-time thermal-mechanical controller to be used for beamline optics in high-power light source radiation facilities. While the obtained performance could theoretically be expected to be very high, under real conditions some practical limits are anticipated, the most obvious being the dynamic response of the temperature sensors. Secondly, a validation setup using a high diffusivity material was built, calculated, and measured, and the sensors dynamic response was extracted from the comparison between numerical and experimental results. Thirdly, this sensor model was included into the realtime controller model, and the updated performance was estimated.

As a conclusion, it was found that in this experiment, thermal probes not only induced an additional delay but also some filtering effect. A further question of general interest would be to know if those effects primarily stem from the thermal paste or from the sensors themselves. Such a study will require systematic investigations, beyond the scope of the present study. A pragmatic approach for the commissioning of such systems would be to systematically measure the thermal FRFs, and tune the control parameters accordingly, so that that maximal performance and sufficient stability are guaranteed.

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