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Design principles for ultimate mechanical stability

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Abstract
When extreme mechanical stability is required, the well-known design principles of thermal centers and low expansion materials are effective tools to cope with uniform temperature changes. However, they are generally insufficient when local heat sources are involved. The low thermal conductivity of materials such as Invar or Zerodur induces large temperature changes and gradients. Additionally, expansion differences between connected components induce interface stresses which can lead to deformations and/or interface slip. As part of the JPE competence development program, solution strategies to these challenges have been developed and used in multiple high-tech applications.

For certain systems it is beneficial to accept a higher thermal sensitivity in order to reduce temperature changes and/or settling time. In these cases, a more comprehensive system view is required which balances (low) thermal sensitivity with other design aspects such as thermal management, well-defined interfaces, and coping with differences in expansion between components.

This work quantifies the differences between these design approaches by comparing two alternative implementations of an optical cavity. A reference cavity is designed by employing a conventional approach of minimizing thermal sensitivity. The second design applies materials which balance expansion, conductivity, and thermal capacity. Additionally, interfaces are decoupled with flexures and the temperature is actively stabilized using a thermoelectric cooler. These design principles are widely applicable throughout the field of precision engineering.

The relative performance of these two approaches is quantified in a technology demonstrator. In this setup, the two cavities are disturbed by an equal, local heat source. Interferometer measurements show that an order of magnitude improvement in stability and settling time is feasible with the advanced approach. For showcasing the demonstrator, the sensors are replaced by a Fizeau interferometer setup. The real-time deformations of both cavities are visualized by projecting fringe patterns onto a viewing screen.

Design principles, Stability, Precision mechanics, Thermal control, Opto-mechatronics

1. Introduction

In high-end (opto-)mechatronic systems the positioning performance is often affected by mechanical stability of critical components. Examples range from misalignment or deformation of optical components, to drift in the metrology loop of a motion platform. On medium to long time scales (minutes to months), this stability is often dominated by thermal effects. Mechanical stability can be achieved by applying well known design principles such as low expansion materials (Invar), well-defined interfaces, or thermal centers. These are effective measures when dealing with uniform temperature variations, e.g. from ambient temperature fluctuations. However, many precision systems also include local, time-varying heat sources such as dissipating sensors and motors, light absorption by mirrors and lenses, or adiabatic heat loads due to vacuum pump-down. To maintain extreme stability under such conditions JPE has developed advanced solutions as part of its competence development program. This work showcases several design principles for advanced mechanical stability by applying them to a simplified optical system consisting of an aluminum mirror and a glass disk (Fig. 1). The goal is to achieve a stable distance between two optical components and maintain this stability in the presence of local, time-varying heat loads.

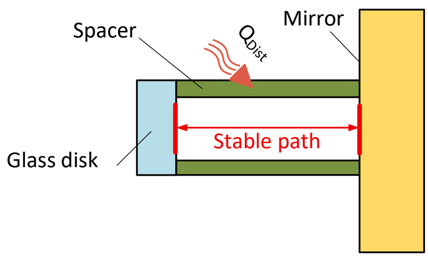

Figure 1. Schematic depiction of a simplified optical system with a glass disk and aluminum mirror. The objective is to stabilize the distance between the backside of the glass disk and the mirror surface.

2. Design approach

The reference design is based on the conventional approach to minimize the thermal sensitivity of the system, i.e. minimize the deformation resulting from a given temperature change. The thermal expansion is described by the following formula:

$$\Delta L = \alpha L \Delta T$$

Hence, to minimize the deformation for a given temperature change, the length L and the Coefficient of Thermal Expansion (CTE) α must be minimized. This is done by connecting the disk directly to the mirror using an Invar spacer (Fig. 2). The spacer is clamped to the mirror with a statically determined 3-point interface, preloaded with a high bolt force. This creates an interface which has a high stiffness and a low thermal contact resistance. The high preload force reduces the risk of (micro) slip due to expansion differences between the two components.

The glass disk is glued to the front of the spacer. Glass beads are mixed in the adhesive to create a well-defined bond layer thickness. Stability is improved further by applying an adhesive which is geometrically stable due to a low water absorption and low outgassing rate. The disturbance heat is removed via a passive heat sink at the backside of the mirror.

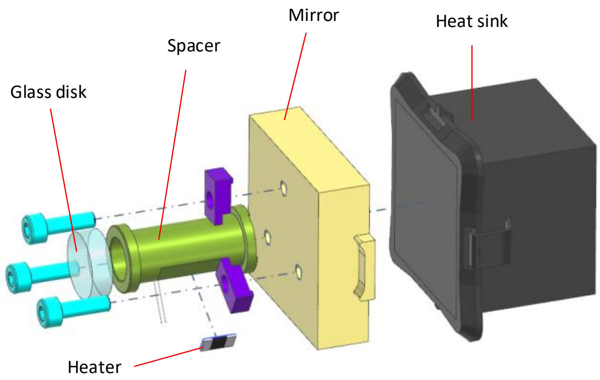

Figure 2. Optical system design which minimizes thermal sensitivity.

On the second system, a more holistic design approach is applied (Fig. 3). This focuses on the thermal management of the system instead of relying on low expansion coefficients.

The spacer connecting the two optical components is manufactured from Tungsten-Copper (WCu). This material has a higher CTE than Invar (~4x higher), but also a higher thermal conductivity (~20x higher). This results in an improved thermal and mechanical stability. An additional benefit of this material is that the CTE is close to that of the N-BK7 glass disk. This leads to smaller expansion differences, and thus lower stresses in the adhesive connection.

The higher thermal conductivity also leads to a significantly smaller thermal time constant. This faster reaction time allows for the active stabilization of the temperature by a PID controller. The temperature of the spacer is measured by a temperature sensor (PT1000) and used to control the heat flux of a Peltier element at the backside of the mirror. The control is implemented by a Meerstetter TEC-1089 temperature controller. A heat sink with fan cools the hot side of the Peltier element.

The mechanical stability in this design is further improved by placing the adhesive in defined glue pockets, instead of between the two components. This way, the glass disk and spacer are in direct contact with each other. Any deformations of the adhesive due to creep or thermal expansion do not directly affect the position of the disk.

Flexures are machined on each end of the spacer. The radial compliance allows for independent thermal expansion of the different components without introducing high interface stresses which may lead to (micro) slip. By placing the flexures symmetrically around the center axis, the thermal center of the system is preserved.

Both systems are mounted to a baseplate via an interface post at the bottom of the mirror. The thermal disturbance is applied by a resistor glued to each spacer.

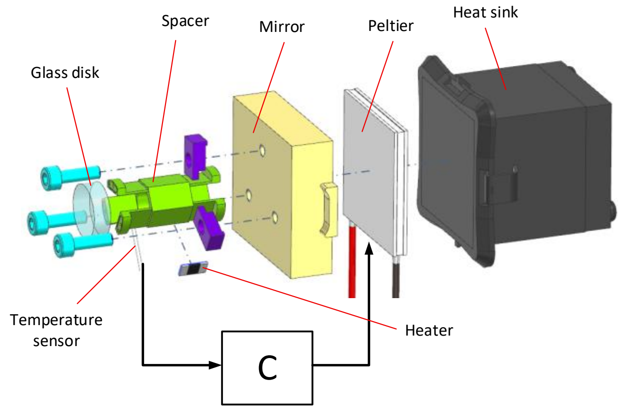

Figure 3. Optical system design which employs advanced stabilization principles.

3. Performance analysis

3.1. Modeling methodology

Each optical system is modelled with a lumped capacity thermal model consisting of 9 nodes (Fig. 4). First, the geometry of each component is approximated by a block, cylinder, or tube of representative dimensions. Nodes are defined within each component. The spacer and mirror have 2 and 3 nodes respectively to model temperature gradients within these components. The simplified geometries are used to derive the thermal capacity of each node, as well as the thermal conduction resistance between nodes. Estimates for thermal contact resistances are included for the bolted interfaces between components. Interface resistance for the adhesive connection between nodes 6 and 7 is neglected, but the conduction resistance of the adhesive bulk is included in the model.

The model contains two fixed temperature nodes. All nodes have a convective heat transfer to the surrounding air (node 8). The system is connected to a fixed temperature base frame (node 9) via the mechanical interface (node 1).

Two heat inputs are defined. The disturbance is injected at the spacer (node 6). Heat is removed at the backside of the mirror (node 2) which represents either the passive heat sink, or the active Peltier element.

The capacity matrix, conduction matrix, boundary condition nodes and heat input nodes are used to rewrite the system in state space description. This allows for simulation of the nodal temperatures due to time-varying heat inputs.

For the 'advanced stabilization' case, a PID controller is tuned which controls the heat flux of the Peltier element (node 2) based on the temperature measured by a temperature sensor at node 6.

The nodal temperatures are modelled in the time domain for both systems. Finally, the temperatures of the spacer nodes are used to calculate the length change of the spacer due to thermal expansion.

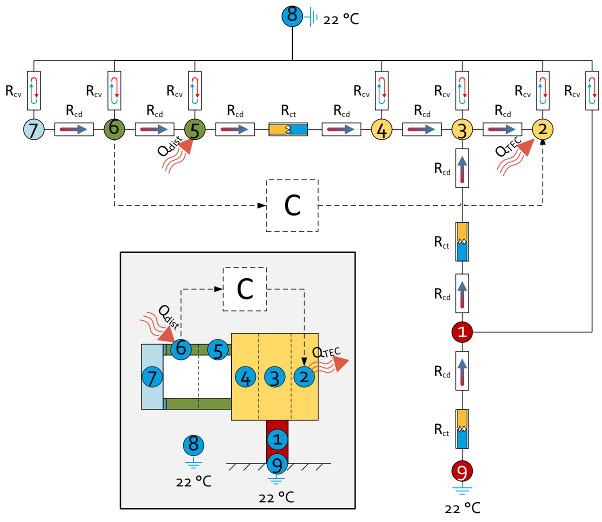

Figure 4. Lumped capacity thermal model with 9 nodes.

3.2. Modeling results

For each design approach, a 2 W constant disturbance is applied for one minute. After this, the disturbance is removed and the systems are allowed to settle. Figure 5 compares the results of the two design approaches. Three distinct differences can be observed in the results.

First, despite the significantly lower thermal expansion coefficient of the 'Minimize Sensitivity' design, the peak deformation is significantly larger than in the 'Advanced Stabilization' case. This is the result of the low thermal conductivity of Invar compared to the WCu. This results in a factor 6 larger ΔT for the Invar spacer, completely negating the gain of the lower CTE.

Second, the 'Advanced Stabilization' approach is able to achieve a steady state situation significantly faster compared to the 'Minimize Sensitivity' approach. This is possible due to the factor 20 higher thermal conductivity.

Finally, both systems do not converge to the same equilibrium state. In the 'Minimize Sensitivity' system, a constant disturbance causes the system to converge to a non-zero equilibrium state. The active system, however, controls the temperature, and resulting deformation, back to the desired setpoint. This way the original cavity length is maintained, despite slow varying disturbances.

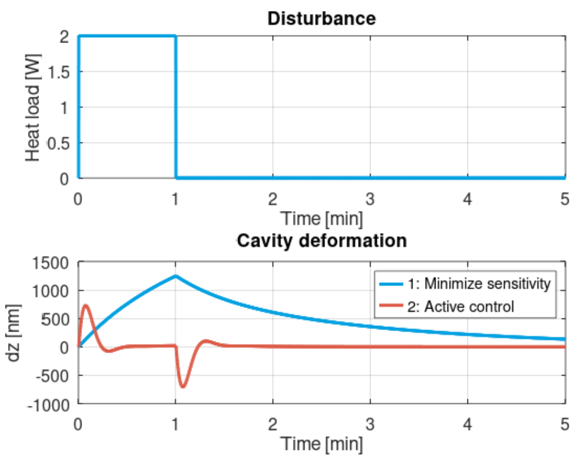

Figure 5. Results of thermal state space model. Input thermal disturbance profile (top) and resulting cavity deformation (bottom) for both design approaches.

4. Realization

Figure 6 shows the realized optical systems. The 'Minimize Sensitivity' design is visible on the left. Note that a fan is mounted to the passive heat sink to shorten the settling time in between experiments.

The 'Advanced Stabilization' design is shown on the right side of Figure 6. Note that this design uses a larger heat sink and fan as not only the disturbance heat, but also the internal power dissipation of the Peltier element has to be extracted.

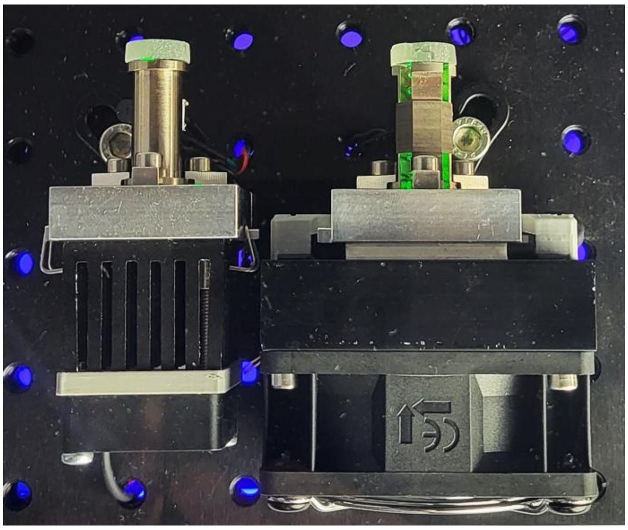

Figure 6. Close-up of the realized setup with the two alternative designs. 'Minimize Sensitivity' (left) and 'Advanced Stabilization' (right)

5. Measurements

5.1. Measurement methodology

After realization of both systems, the performance is quantified using the measurement setup shown in Figure 7. Before the glass disk is glued to the spacer, an interferometer sensor head is clamped to the spacer. By measuring the distance to the aluminum mirror, the mechanical stability of the spacer is quantified under the influence of the thermal disturbance.

The sensor measures not only the thermal expansion of the spacer, but also of a part of the titanium sensor head itself. To reduce this effect, the sensor head is thermally decoupled from the spacer by small ceramic insulators. These have a high thermal resistance, while providing decent mechanical stability due to the high stiffness and low thermal expansion coefficient.

A temperature sensor is mounted on the sensor head (not visible in Figure 3) to measure the temperature change of the sensor head directly and compensate for the remaining thermal expansion in post processing.

The heater is connected to a power supply to provide a 2 W disturbance for 1 minute. Due to limitations of the Peltier controller output power, the disturbance is switched on and off with a 0.4 W/s ramp.

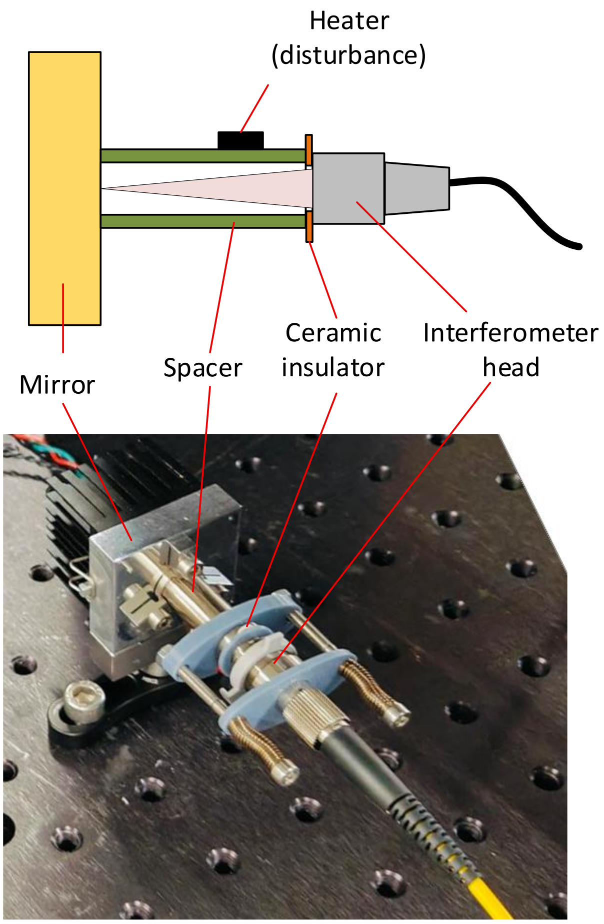

Figure 7. Schematic depiction of cavity length measurement setup (top) and photograph of realized setup (bottom).

5.2. Measurement results

The results of both measurements are plotted in Figure 8. Overall the measured deformations show a similar profile compared to the simulated results of Figure 5. There are, however, several differences.

The total magnitude of the deformation is approximately 3 times lower than in the simulation. The measured disturbance power is electrical power dissipated in the heater element. Due to the limited conductivity of the adhesive used to connect the heater to the setup, a significant fraction of this power is likely lost to convection with the surrounding air. Furthermore, the convective heat transfer from all outer surfaces to the surrounding air is included in the model, but likely underestimated as the large fan of the active heat sink induces forced air flows around both setups.

The additional thermal resistance of the heater adhesive is also observable in the temperature and deformation graphs. The smoother response compared to Figure 5 indicates an additional thermal resistance between the heater element and the spacer.

The temperature response of the active controlled case is slower than in the simulation as the controller has been tuned less aggressively in the realized system. This is done to limit the peak currents drawn by the Peltier element on the flanks of the disturbance.

The stability in the interval from 100 seconds to 200 seconds is 4 nm, while the Minimize Sensitivity setup drifts 230 nm.

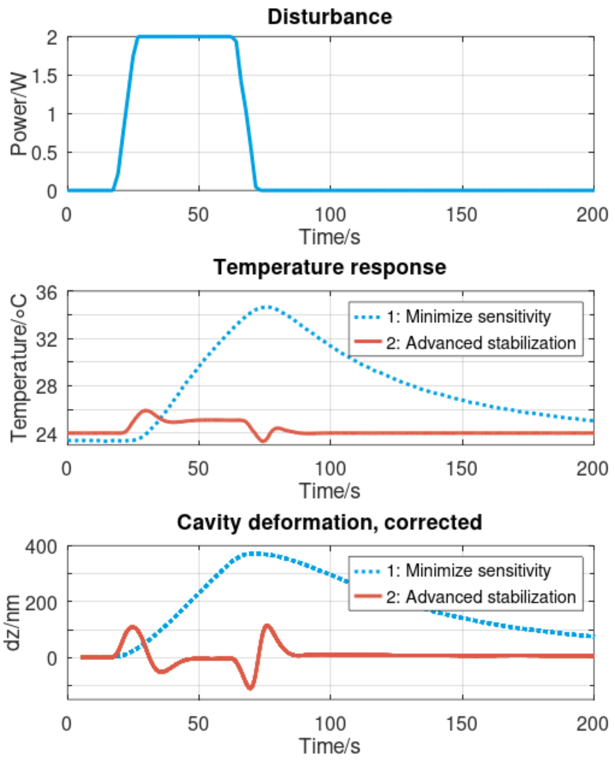

Figure 8. Measurement results with applied disturbance heat flux (top), measured spacer temperatures (middle), and measured cavity deformations (bottom).

6. Conclusion

Minimizing the thermal sensitivity of the critical parts in high-precision applications can be an effective method to achieve high mechanical stability. There are, however, cases where such an approach does not suffice, and a more comprehensive system view is required. This is especially true in situations where local, time-varying disturbances are present in or near the critical components.

This work presents various design solutions that improve thermomechanical stability in high-tech systems. A conventional precision engineering approach that uses low expansion materials is compared to an advanced approach which balances thermal properties and employs active temperature control. The second approach results in an order of magnitude improvement of the settling time and up to an order of magnitude improvement of mechanical stability.

The advanced method actively stabilizes the temperature instead of minimizing the sensitivity to the existing temperature variations. It is therefore a significantly more effective method of decoupling the thermal system behavior from its surroundings. This results in a considerable improvement of the long-term mechanical stability.

The presented design principles are applicable to all precision engineering fields, including semiconductor, defense, space, or metrology.