EMRP - IND13: Thermal design and time-dependent dimensional drift behavior of sensors, materials and structures

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Good Practice Guide on "Locating and control of cooling devices on thermal sensitive equipment."

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1. Focus of Guideline

This guideline is written for stakeholders that are concerned with or plan to cool down or thermally stabilise thermally sensitive parts of complex precision engineering equipment. It aims to provide information of advantages and disadvantages of some cooling approaches. It gives hints for choosing the suiting approach and shows their limits of application and precision of their results.

2. Properties of thermal cooling approaches

In general, precision measuring and precision manufacturing instrumentation should be designed in compliance with some well-known design rules:

- Heat sources like drives or electronic devices should be placed far away from thermally sensitive parts or the object of investigation
- Thermally low conducting materials should be used to reduce heat flow into thermally sensitive parts (high temperature gradients occur)
- Thermally high conducting materials should be used to guide heat to heat sinks or thermally insensitive components
- Materials with low coefficients of thermal expansion (CTE) should be used where high temperature gradients occur
- CTE of materials of joint components should be suited
- The mechanical design should be symmetric to heat sources to get symmetric dimensional deformations rather than tilting or torsion
- …

In many cases not all design rules can be respected in a design and significant influences from temperature and temperature gradients on the instruments remain. In these cases typically additional cooling is used to improve the situation. Here, one can distinguish between active and passive cooling.

2.1. Active cooling

In active cooling approaches actively controlled heat sources or heat sinks are used to control or stabilise the temperature of a component or instrumentation. Typical sources or sinks which are utilised are peltier elements, electrical heaters, stirling motors or heat pumps. Typically, they are applied in combination with heat exchangers to temper working media like gases or fluids, which exchange the heat with the components to be stabilized. In some cases the active sink can be coupled directly without using working media to the component [1].

Active cooling approaches offer certain advantages. The temperature at the position of interest can be controlled directly, different types of sinks with different power are available and the power of the exchanged heat can be adjusted. But, applied to precision dimensional measurement instrumentation they also have drawbacks. Most of the types of sources contain moving or rotating parts which can cause mechanical vibrations in the measurement instrumentation. These vibrations can cause dimensional measurement errors, especially when uncertainties at the nanometer level are targeted. The moving working fluids in pipes or even ventilating air can be a source of disturbing vibrations either. The application of active cooling approaches requires knowledge in controller design, models of the controlled system and certain equipment.

2.2. Passive cooling

Constructive changes in the instruments which are made to optimise the paths of heat flow or to minimise the thermal sensitivity of the set-up one can summarise under passive cooling. Here, by means of constructive changes the parasitic heat is guided away to thermally insensitive components or to the environment. The thermal optimisation is realised without active controlling or influencing of heat sources.

The starting point of a thermal optimisation is a sufficient understanding of the heat transport phenomena or temperature fields in the instrumentation. They can be acquired by means of temperature measurements or by thermal modelling and simulation of the instrumentation.

The advantages of passive cooling approaches are a reduced effort compared to active cooling approaches, no electronics, controllers and sensors are needed and no mechanical vibrations occur. Disadvantageous are a usually minor cooling power compared to active approaches, resulting temperatures which are depending on the boundary conditions and temperature deviations which will not equal to 0 K.

3. Locating cooling devices

The optimal position for a cooling device fulfils some of the following criteria:

- It is close to the source of parasitic heat,
- It is far away from equipment which is sensitive to thermal or mechanical perturbations which might be coupled in from the cooling device,
- The parasitic heat can be guided away from the sensitive areas without further interfering the ,
- The source is coupled to thermally well conducting materials to enable a maximal heat exchange with the source/ sink
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Some of the criteria are antithetical, wherefore not every criteria can be met. Hence a general advice for the placement of the cooling devices cannot be given. Rather, the optimal place and method should be estimated by preliminary considerations, thermal modelling of the equipment or comparison measurements.

4. Controlling cooling devices

Often, a thermal control of heat sources or thermally compensating heat sinks is necessary to achieve a thermal stable operation of complex measuring and engineering equipment. For this, the appropriate controlling approach, the structure of the control loop and the applied control algorithms depend on the specific constructive and thermal conditions, wherefore general hints and advices for building of a thermal control cannot be presented in this guideline.

Within the context of the EMRP project a controlling infrastructure was developed and tested, which can be applied for complex equipment with several heat sources.

If several inputs (heat sources, boundary conditions) and observers/ monitoring points (temperature sensors) need to be regarded, the systems to be controlled are of MIMO-structure. Here, a standard SISO-controlling of the sources by means of classical PI- or PID-controllers get to their limit, especially when a coupling between each input and several outputs is relevant. Instead of this, controllers for MIMO-systems need to be applied. In those cases, a description of the system in state-space-representation is useful. These state-space-models should be of low order *n*, typically $n \leq 10$, to enable a well handleable and quick data processing and controlling.

One method to estimate such low order models (LOM) of the complex equipment is the Modal Identification Method (MIM). It uses data obtained either from measurements recorded on a real equipment (one thus talks about “experimental modelling”) or from simulations performed with a large-size reference model, also called detailed model, such as a Finite Element model. The MIM therefore aims to adjust the LOM constitutive parameters using optimization techniques, in order for the LOM to mimic the data characterizing the input-output dynamics of the system [1].

For controlling of heat sources and sinks, the application of a state feedback control using a Model Predictive Controller (MPC) or Linear Gaussian Quadratic Regulator (LGQ) has been found to be favorable. In this control, the LOM and the known input quantities (heat load) are fed to a Kalman-filter which estimates the state of the system to be controlled. MPC and LGQ can be applied to non-linear systems, too.

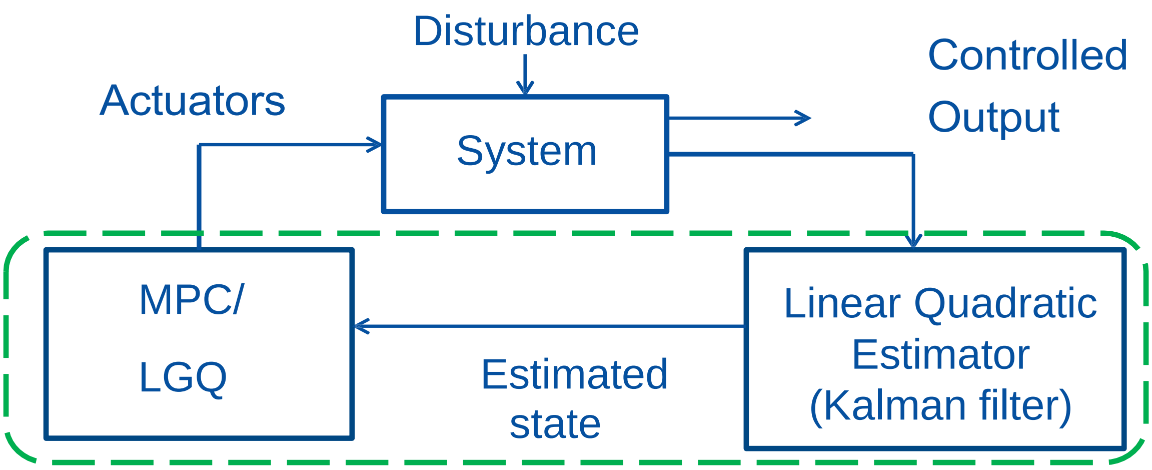

Figure 1 - Control scheme for MPC or LGQ [1]

The detailed mathematical description of the controlling algorithms is not the aim of this guide. It can be found at free accessible sources [3, 4]

5. Literature

[1] http://projects.npl.co.uk/T3D/documents/20140319-20_euspen_schalles.pdf

[2] http://projects.npl.co.uk/T3D/documents/tempmeko-presentation.pdf

[3] http://ebook.download2.net/m/model-predictive-control---stanford-university-w44100.html

[4] http://www.pdfdrive.net/linear-quadratic-regulator-e7505404.html