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High accuracy downstream temperature control using a local heater

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Abstract

Thermal effects have a significant contribution drift of high-precision systems. Temperature fluctuations can occur due to varying heat loads in the system. These fluctuations cause deformation of critical system parts, which result in undesired loss of accuracy and drift. Although these high-precision systems are conditioned with cooling water with millikelvin temperature stability, this cooling water may be heated during transport due to ambient variations and local heat loads. These temperature fluctuations result in deformation of critical machine parts, loss of accuracy and drift. In this paper a solution using an additional sensor and a cascaded feedback controller is presented, which is able to suppress static offsets and slow variations at the downstream sensor. This can be used for conditioning of sensitive machine parts without offset, while maintaining millikelvin temperature stability.

Thermal control; Local heater; Local disturbances; Additional sensor; Cascaded control;

1. Introduction

Thermal effects have a significant contribution to the drift of high-precision systems. Temperature fluctuations can occur due to varying heat loads in the system. These fluctuations cause deformation of critical system parts, which results in undesired loss of accuracy and drift.

The conventional solution is to supply machines with water from a chiller, which has a few disadvantages. Firstly, the temperature stability of commercial chillers (tens of millikelvin) is often insufficient. Moreover, the chiller is typically placed far away from the system, which limits the response time to disturbances. Finally, only one temperature setpoint can be given, making it impossible to act on local disturbances.

For high-end systems it is desirable to have local thermal control to anticipate on different local heat loads and their cooling requirements. Therefore, multiple controlled local heaters can be added in the water channels, which enables individual temperature control in each channel. These local heater devices can be small, i.e. small thermal mass. Therefore, the dynamics can be optimized to obtain a higher bandwidth and better disturbance rejection of the control loop.

To control the temperature of the overall system, three sensors are used. The feedforward and feedback sensor inside the local heater device are used to generate water with millikelvin (mK) temperature stability. In order to achieve the desired temperature stability, the dynamics and transport delays of the local heater device are characterized.

Often it is impossible to place a local heater device close to the machine, therefore the water needs to be transported to the machine. Moreover, active machine parts generate local heat loads on the system. Both ambient and heat load variations cause temperature fluctuations of the cooling water. Although these disturbances are typically very slow, these can cause relevant deformations and/or loss of accuracy by drift in the system. To achieve stability in the millikelvin-range at the system an additional feedback loop is employed, which utilises an additional sensor near/on the system to correct for offsets and slow variations. This results in a system with millikelvin temperature stability, which can compensate offsets and slow temperature variations at a relevant location for the accuracy of the system.

2. Problem statement

For high-precision systems cooling water with high temperature stability, i.e. low standard deviation, is required as temperature variations cause loss of accuracy and drift.

First of all, the water chiller is typically placed far away from the machine to be conditioned, e.g. in the basement. During the transport of the water the temperature of the water will change as a consequence of the difference between water and ambient temperature. Even when the tubes are insulated, the water will follow the slowly varying ambient temperature with a certain sensitivity (order of milliKelvin per Kelvin). Faster ambient temperature variations will be filtered due to the insulation around the tubes. Secondly, local heat loads cause undesired deformation of critical machine parts.

Both ambient variations and local heat loads can cause undesired temperature fluctuations of critical machine parts. Therefore, it is desired to feed these critical machine part with cooling water with millikelvin temperature stability (3σ) and to compensate for these local temperature fluctuations.

3. Control strategy

To achieve the requirement from the previous section the following control strategy for the local heater is proposed, which consist of 1) *an inner control loop* in the heater unit to achieve water with millikelvin temperature stability, and 2) *an outer control loop* using a downstream sensor. This is known as cascaded feedback control [1], i.e. the outer loop generates a setpoint for the inner-loop, which maintains the temperature stability. Using such heaters, the water can only be heated, which is much faster and simpler than cooling. Moreover, cooling of such a small volume would be infeasible.

An alternative approach would be to use the downstream sensor for direct feedback. However, this approach has a few disadvantages. The transport delay, which can be directly linked to the bandwidth and performance of the system, is dependent on the tube length. Together with the expected disturbance spectrum this leads to a deteriorated performance.

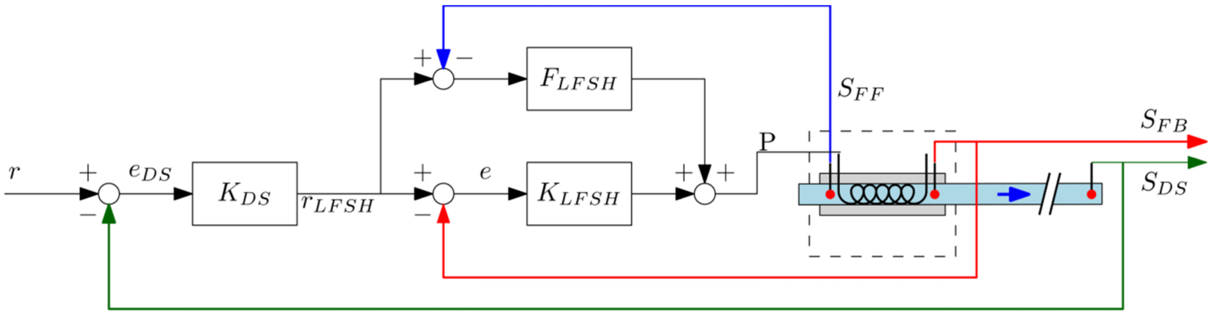

Figure 1. Control scheme for downstream offset control with inner-loop to maintain temperature stability and outer-loop to correct for offsets and slow variations on a downstream sensor (S_{DS}) location near or at critical machine parts.

3.1. Control of the local heater unit

The inner-loop controller in Figure 1 consists of two parts, a feedback and feedforward controller, K_{LFSH} and F_{LFSH}, respectively. The feedforward controller uses a measurement of the incoming water to heat the water, the feedback controller corrects for disturbances and feedforward mismatch using the outgoing water temperature of the local heater unit.

The dynamic properties of the plant are a function of the nominal flow, which is fixed at 2.5 l/min. To tune these controllers the plant dynamics and transport delays have been characterized using frequency response identification and step response measurements [2].

3.2. Downstream offset control

The goal of the outer loop controller, K_{DS} in Figure 1, is to minimize the temperature offset at the downstream sensor S_{DS}, which is located close to the critical machine part. In this way, temperature offsets and slow variations, e.g. ambient variations can be corrected for. Of course, the bandwidth of the outer loop controller is limited by the transport delay of the water between the local heater unit and the downstream sensor. This depends on the flow, tube length and -diameter. Therefore, it is advantageous to place the local heater unit as close as possible to the critical machine part.

4. Results

4.1. Experimental setup

The experimental setup to mimic the scenario of high-precision equipment with a downstream sensor is shown in Figure 2. Here a 2nd local heater unit, located at a distance of approx. 2 meter of the 1st local heater unit, is used to apply a 30W step disturbance just before the downstream sensor. Of course this step disturbance is a non-realistic worst-case scenario; typical ambient variations and local disturbances will be of a much slower nature.

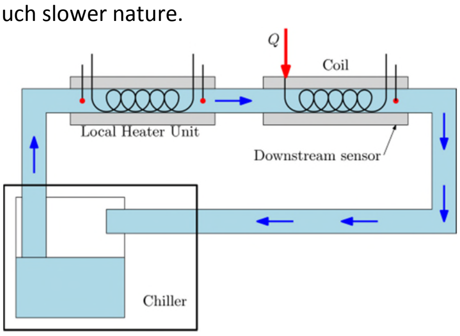

Figure 2. Experimental setup (schematic).

4.2. Downstream step disturbance

The result for a 30W step disturbance is shown in Figure 3. Here, it can be seen that the LFSH setpoint is updated as soon as the disturbance is visible on the sensor. However, it takes a few seconds before disturbance rejection is visible due to the transport delay. At 30 s the disturbance is fully rejected, i.e. no offset remains. At 40 s the disturbance is removed again, leading to a negative offset. This offset is regulated to zero after approximately 30s.

4.3. Temperature stability of downstream control

The temperature stability using downstream control has been measured for one hour. During this temperature stability measurements no external disturbances are applied to the system. The temperature results are shown in Table. 1.

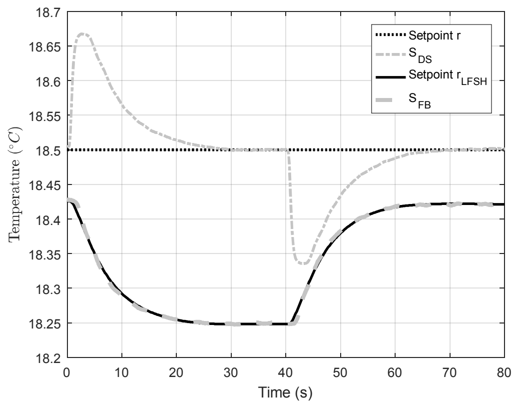

Figure 3. Results of 30W downstream step disturbance.

Sensor	Standard deviation σ
S_{FB}	1.5 mK
S_{DS}	1.3 mK

Table 1. Temperature stability using downstream control

5. Conclusions

In this paper a control strategy for thermal control using a local heater has been presented. Using the proposed method it is possible to achieve cooling water with milliKelvin temperature stability and without any offset on a downstream location. The controller can compensate for relatively slow ambient variations and local heat loads near the critical machine parts, possibly leading to improved accuracy and lower drift. Future work includes compensation strategies for a priori known local disturbances using feedforward control.

References

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[2] Pintelon R and Schoukens J, *System Identification: A Frequency Domain Approach,* March 2004, IEEE Press, New York