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Modelling & Identification for Thermal Control of Cooling Water with Varying Flow

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Abstract
Thermal effects can have a significant impact in precision engineering applications. To reduce this impact, thermal conditioning of the system via circulating water can be applied. The accuracy with which a system can be conditioned depends on the temperature variations of the water. A heater system with temperature sensors has been designed to enable active control of the water temperature. This system has shown to achieve millikelvin accuracy. With the aim of achieving this accuracy over multiple flow rates, modelling and identification techniques are explored and applied. This work forms a basis on which controllers can be designed that can attenuate temperature disturbances over a wide operating range.

Thermal Modelling, Identification, FRF, varying flow

1. Introduction

For high precision systems, thermal effects can have a large impact on performance. Changes in temperature can cause deformations of critical components within a system, reducing the system's accuracy. Thermal control is therefore desired to counteract these fluctuations and condition the temperature of the system components. Previous approaches achieved millikelvin temperature control [1], using a local fluid stream heater shown in figure 1. With a local fluid stream heater (LFSH), circulating cooling water can be thermally conditioned. Although important developments have been made to achieve the results in [1], at present the accuracy cannot be obtained for varying flows. The aim of this paper is to achieve the performance in [1] for a large range of varying flows. To achieve this next level of resilience, it is important to understand the effect flow variations have on the system. A combined approach of modelling and identification is used to determine the thermal behaviour of the LFSH. With an accurate and verified model, new controllers can be designed to ensure temperature stability for a wide range of flows, whilst attenuating temperature fluctuations disturbing the system. Different modelling approaches exist for thermal systems, so approaches are compared. The desired model properties for controller design are sketched. Since an accurate model of the existing setup is desired, the step towards identification is made. Using the insight and results from the modelling process, high accuracy identification is made possible. Using existing identification techniques, the system dynamics can be identified for varying flow rates, resulting in a set of models. These models can then be combined into a linear parameter varying (LPV) model that fully describes the LFSH dynamics. Results of this work are analysed and its applicability in future work of this research is shown.

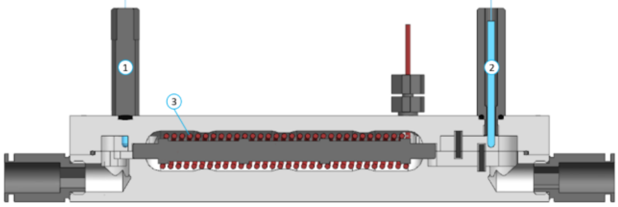

Figure 1. A cross-section of the Local Fluid Stream Heater used in this research, with incoming temperature sensor (1), outgoing temperature sensor (2) and heater coil (3).

2. Modelling

Thermal systems typically have slow transient behaviour and dynamics at low frequencies compared to the electrical and mechanical dynamics in precision mechatronics. Within the LFSH, an important and dominant factor is the mass flow of water.

2.1. Analytic Modelling

An initial approach is to model the behaviour from first principles of heat and mass transfer. The elegance of this approach is its physical origin, where the formulae arise from describing the heat transfer via conduction, convection and radiation [2].

Despite this being a good starting point when describing the thermal properties of a system, there are multiple drawbacks to this approach. The size and complexity quickly grows with nontrivial geometry, making it near impossible to fully model and simulate a system. Just describing the fluid dynamics and flow of water through the heater is worth a study of its own. A multitude of parameters is needed to describe all the materials and their interactions. These parameters are difficult to determine exactly. Therefore, measurements are needed to determine accurate parameters and validate the model. The question also arises to what accuracy the system needs to be described and if by simplifying and/or assuming simplified properties similar results can be achieved, since parameters are calibrated to fit the model on data.

2.2. Lumped Mass Modelling

Lumped mass modelling, also called the lumped capacitance method, is an attractive way to model heat transfer. A material is divided into multiple smaller masses for which it neglects temperature gradients within the lumped masses, allowing linear modelling of the thermal dynamics [2]. The linearity of these models make them computationally viable and thus allows for fast simulation and analysis. Transient behaviour is captured in these models and mass flow can be added as an additional interaction.

The maximum mass size for which internal temperature gradients can be neglected, is determined by the ratio between the internal thermal resistance and the thermal resistance to its surroundings [2]. This ratio is called the Biot-number, and it depends on the material properties and the thermal interactions of the mass. A possible drawback can be that the amount of lumped masses becomes large for certain systems and consequently also the model size becomes impractically large. Furthermore, a solid is modelled as multiple lumped masses in series with heat transfer between them, giving first order dynamics between lumps. This first order behaviour comes with a 90° phase lag for between adjacent masses. A series connection results in a multiple of this lag dependent on the amount of masses. This means that the overall modelled phase relation is ambiguous, with increased phase lag for an increased amount of lumped masses. Experimental validation can be used to ensure accuracy of the model. Similar to the analytical approach, the multitude of parameters describing the system can then be calibrated to fit the model to the measured data.

2.3. Desired Model

The desired result of the modelling process is a model that can capture the thermal dynamics and heat transfer from the incoming water temperature and heater coil to the outgoing water temperature. The model should be sufficiently complex to capture the relevant dynamics between these points, but also have restricted complexity to facilitate computation. A low order model can also allow for more advanced controller designs, like H-infinity control, for which the order of the controller is minimally as large as the modelled plant. The model is also required to take varying flow into account.

For all modelling approaches, it is beneficial to validate and tune the model using measured data to ensure accuracy. Since the accuracy then depends on measurement, a data-driven approach can be beneficial.

3. System Identification

System responses can be obtained from measurements via system identification. Commonly, the frequency response function (FRF) is estimated. By designing the experiments with carefully selected frequency content, the response can be measured at the output. FRF identification is fast, inexpensive and accurate [3]. Little to no knowledge or modelling is needed to obtain an estimate of the response, although it can be used to improve the accuracy.

FRF identification assumes a system to be in steady state, which often is not the case. Thermal systems often have a large transient response, meaning a significant amount of time is needed to reach a steady state. Therefore, identification techniques that take the transient response into account are desired. The Local Polynomial Method (LPM) approximates the local transfer function by a polynomial such that the transient can be estimated and removed [4]. This method can be generalized into the Local Rational Method (LRM), which uses a rational function for the local approximation [5]. By using a rational function, linearity is lost in the parameters, but improved estimation quality is shown [6]. This approach can be further improved by incorporating system knowledge of the system poles (LRMP) [3]. Other interesting extensions include identification of linear parameter varying system (LPV-LRM) [7].

Temperature control for varying flows is desired, and thus identification of the plant for varying flows is needed in accordance. Combining the identification and modelling over a range of flows, an accurate model of the system can be obtained.

4. Results

A lumped mass model has been constructed describing the LFSH consisting of 220 states. The frequency response from the inserted coil power to the outgoing water temperature is evaluated for multiple flow rates in figure 2. The figure shows that both the magnitude and phase change for varying flow. For comparison, the magnitudes at low frequencies at 1 l/min and 10 l/min are 0.0135 K/W and 0.0014 K/W, respectively. This is near a factor ten difference. With ten times the amount of water flowing through the system, it is to be expected that ten times the power is needed for the same temperature change.

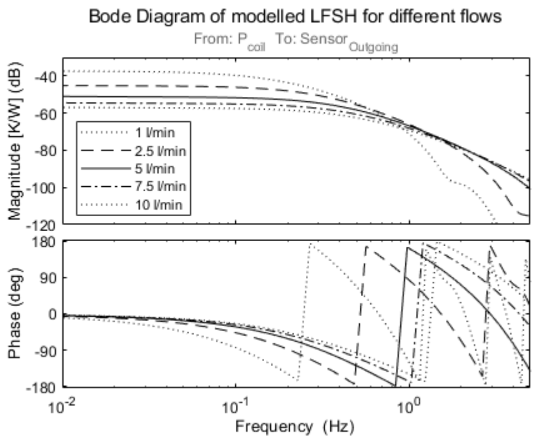

Figure 2. Frequency response from the coil power to the outgoing water temperature of the LFSH for multiple flow rates.

5. Conclusion and Outlook

Multiple modelling and identification techniques are researched and compared. By modelling the system using its physical parameters, the effect of parameter variations can be analysed. It is shown that the flow rate has a large impact on the dynamics. This insight can be used to define input signals and settings for the experiments used to identify the system.

It is concluded that the combined approach of modelling and identification provides accurate estimates of the responses, allowing controller design that can adapt to flow variations in ongoing work.

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