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Research Paper

Experimental thermal regulation of an ultra-high precision metrology system by combining Modal Identification Method and Model Predictive Control

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HIGHLIGHTS

- Compact set-up simulating the behaviour of a new high precision cylindricity machine.
- Thermal evaluation of a compact ultra-high precision set-up is proposed.
- Reduced Models (RM) are built using Modal Identification Method from experiment.
- Thermal control of the set-up is proposed using Model Predictive Control approaches.
- Regulation of the thermal drift inside the set-up to less than 0.01 °C using the MPC.

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ABSTRACT

Thermal drifts caused by the power dissipated by the mechanical guiding systems constitute the principal limit to enhance the measurement uncertainty of an ultra-high precision cylindricity machine. For this reason, an ultra-high precision compact prototype has been designed to simulate the behaviour of the instrument. It ensures in-situ calibration of four capacitive displacement probes by comparison with four laser interferometers. The test bench includes three heating wires for simulating the power dissipated by the mechanical guiding systems, four additional heating wires located between each laser interferometer head and its respective holder to control thermal drifts, 19 Platinum resistance thermometers (Pt100) to observe the temperature evolution inside the test bench and four Pt100 sensors to monitor the ambient temperature.

A Reduced Model (RM) identified from measured data using the Modal Identification Method (MIM) was combined with a Model Predictive Controller (MPC). The control was applied to minimize the effects of thermal drifts on the principal organ of the cylindricity measurement machine. A parametric study of the MPC was initially conducted to evaluate the robustness of the controller. The association of both RM and MPC allowed significant reduction of thermal drifts generated by the three heating wires, which simulate powers dissipated by the mechanical guiding system. The obtained results can be considered as promising with regard to applications in dimensional metrology.

1. Introduction

The French National Institute of Metrology (LNE) is currently developing a new cylindricity measurement machine with a nanometre level of uncertainty, whose design and operational principles are detailed in [1,2]. This research is motivated by the need for better form-error assessment of piston-cylinder assemblies used in gas pressure balances [3,4]. An uncertainty of 10 nm for a 120 mm diameter piston corresponds to a relative uncertainty of 10^{-6} in the pressure measurement. The other main application is the characterisation of commercial cylindricity measuring machines widely used in industry [5].

Thermal perturbations represent the main source of error on machines with a high accuracy level as they induce thermal expansion affecting the measurement accuracy. The negligible anisotropic mechanical dilatation can indeed be considered as an essential

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condition to reach measurement at the nanometre level of accuracy. Several studies were conducted and some of the solutions proposed to reduce the effects of thermal perturbations, include:

- The application of dissociated metrology techniques (DMT) [6,7].
- The selection of materials with high thermal conductivity and small linear thermal expansion coefficient, which allow the thermal perturbations to spread quickly throughout the whole structure leading to a uniform temperature distribution [8].
- The use of an enclosure around the measuring machine to control the effects of the external perturbations (temperature room variation, presence of an operator, etc.) [9].

The application of the above-mentioned principles and precautions is a form of passive control. It helped to reduce significantly the effects of the thermal perturbations generated by homogeneous thermal drifts. For metrology applications at the nanometre level of accuracy, the perturbations induced by non-homogeneous thermal drifts should also be reduced.

To address thermal perturbation issues and reduce their effect to well below 0.01 °C level (and hence limit the dilatation to 1 nm in a 0.1 m long aluminium frame), a real-time thermal regulation system was developed. The most widely used real-time controller is the Proportional Integral Derivative controller (PID), which uses a feedback signal depending partly on the observed error, the rate of change of the error (to damp oscillatory tendencies) and the integral of the error, to ensure high loop gain and therefore long-term stability [10]. However it is best suited to Single-Input Single-Output systems (SISO). More sophisticated control techniques have emerged to control Multiple-Input Multiple-Output (MIMO) systems and the model-based control appears to be the best option among them. Model Predictive Control (MPC) [11,12] and Linear Quadratic Gaussian (LQG) controller can be also cited as examples of model-based control techniques [13–15].

To use one of the above-mentioned methods, a state-space representation of the system to be controlled has to be established. In the field of thermal diffusion, this representation can be derived from spatial discretization (through Finite Elements, Finite Differences, etc.) of the heat equation. The obtained model usually contains a very large number of equations, which makes it unsuitable for real-time control. To overcome this problem, a model reproducing the behaviour of the system but with a smaller number of equations needs to be developed.

Model reduction has attracted considerable attention and many methods have been developed. We are dealing here only with methods based on a modal state-space representation of the system to be controlled [16]. The Modal Identification Method (MIM) is a reduction method developed at Pprime Institute [17]. Thus, a Reduced Model (RM) can be built from knowledge of input–output data, through the minimization of a quadratic criterion. Several applications have been developed on the basis of this method, associated with the Linear Quadratic Gaussian regulator to achieve thermal regulation [18,19].

In this paper, an experimental study is performed to investigate the use of a RM associated to MPC for maintaining the temperature at a constant level within the test bench.

The paper is structured as follows: in Section 2 we present the experimental test bench. In Section 3, we detail the Modal Identification Method used to build a thermal model of the experimental test bench. In Section 4 we describe the control technique used to achieve the real-time thermal regulation. In Section 5 we display and discuss the experimental results of the thermal regulation. Finally we present the conclusions drawn from our work.

2. Experimental test bench

The architecture of the new machine developed by LNE applies the Dissociated Metrological Technique (DMT) [1,2,6,7], which consists in separating the metrology frame from the supporting frame using flexible blades as isostatic links. The metrology frame, which is defined as a conceptual line going through all solids, sensors and joints of the machine likely to influence the measurement uncertainty, passes only through reference and sensing elements. The use of such architecture prevents any force and deformation from being transmitted from the supporting frame into the metrology frame. The topologies of both the reference cylinder and cylindrical artefact are simultaneously sensed by capacitive displacement probes and mutually compared in real time. Therefore, the geometrical stability of the metrology loop depends only on the stability of both reference and probing elements and is neither affected by any deformation of the supporting frame nor by any motional error of the mechanical guiding systems.

The design of the machine perfectly respects the Abbe principle, applies axial symmetry and includes both spatial and temporal redundancy. The XY-translation table using piezoelectric actuators enables *in-situ* calibration of all the capacitive probes of the machine with regard to their respective artefacts.

The capacitive displacement reference probes are located on two levels and symmetrically disposed around the reference cylinder. The use of opposite probes along the *x*- and *y*-axes allows one to compensate the effects of uniform thermal drift (Fig. 1), while the non-uniform thermal expansion of the reference cylinder remains undetected. Nevertheless, from the data provided by a single capacitive probe only the combined error motions and the form errors of the reference cylinder can be detected. In this case, both uniform and non-uniform thermal drifts remain undetected.

The cylindricity measuring machine is located in a controlled environment. However some constitutive elements such as laser interferometers, left switched on permanently to realize *in-situ* calibration of capacitive probes, dissipate heat leading to temperature deviations. Furthermore, mechanical guiding systems used to ensure vertical and rotational motion of the metrology frame represent the main source of thermal perturbation leading to non-homogeneous temperature distribution, which induces thermal expansion in the metrology frame and affects the measurement uncertainty.

An experimental test bench representing the measuring frame – the most sensitive part of the new machine – was developed to investigate new means to attenuate thermal perturbation and drift effects. This test bench was also used to validate the design of the measurement cylindricity machine and to investigate the *in situ* calibration of the probes, the filtering and the stability of the supporting and metrology frames as well as the selection of the operating mode.

The test bench is composed of four capacitive probes ([20–22], Table 1) aligned on a cylindrical artefact, four low power laser interferometers aligned on four independent plane mirrors fixed to the metrology frame (Fig. 2). The metrology frame supports the capacitive probes and is clamped on an XY table via isostatics links (three flexible blades). The XY table is equipped with two piezoelectric actuators under two levels. The motion over a travel range of 80 μm is ensured by four flexible blades, but this range can be increased up to 180 μm. The laser interferometers, which are considered as reference sensing elements, are fixed on the supporting structure with an angular offset of 45° to the capacitive sensors that are fixed on the metrology frame (Fig. 3).

The test bench was equipped with five Pt100 sensors $T_{i=1...5}(t)$ located in the capacitive probe holder, 14 Pt100 sensors $T_{i=6...19}(t)$ located in the supporting frame and four Pt100 sensors $T_{i=20...23}(t)$