Measured thermal modes for thermal design optimization

E.C. Hooijkamp, R. Saathof, F. van Keulen, J. van Eijk
Delft University of Technology, the Netherlands

e.c.hooijkamp@tudelft.nl

Abstract

Reduced thermomechanical models are needed for the next generation precision devices. One of the methods is thermal modal analysis, which decomposes the behaviour into thermal modes and time constants. This study aims to measure these modal parameters. We isolated the behaviour of a single thermal mode exciting the system in the test set-up in this mode. The measured responses as well as the modal contributions are in good agreement with the simulations. Thus, thermal modal analysis can provide a basis for design optimization and compensation strategies.

1 Introduction

The demands on accuracy and speed for the next generation precision devices and machine tools are increasing. The possibility to meet these demands is hindered by thermomechanical problems as they play a major role in the position accuracy [1]. In order to reduce these thermal errors, design optimization and compensation strategies are used. However, they need both accurate and fast thermomechanical models. Many researchers have applied different approaches, but most of these approaches need experimental data to develop an accurate reduced model [1, 2].

Thermal modal analysis breaks the model into a space-dependent and a time-dependent part (i.e., thermal modes and time constants) [3], like the modal analysis in structural dynamics. Accordingly, the model can be reduced by considering only the most physically relevant modes. Besides a reduction method, the concept offers the designer a tool to unravel the complex transient behaviour into separate temperature distributions with a simple behaviour. Thus, these thermal modes and time constants might provide us with a basis for design optimization and compensation strategies. The aim of this study is to illustrate how thermal modes and time constants are extracted from a measured transient thermal response, which is different from the experimental modal analysis as used in structural dynamics.

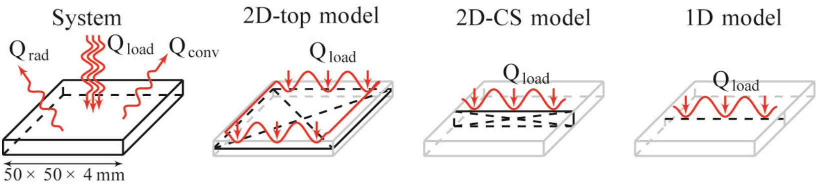


Figure 1: The system and the 2D and 1D numerical models used for the simulations. The shown load is the third symmetric or seventh mode of the 1D model.

2 Methods

We measured the transient temperature distribution of a squared glass sample exposed to a heat load (see Figure 1). An infrared camera was used to measure the temperature distribution of the sample and a projector to expose a variable light (and heat) pattern (see Figure 2(a)). The light pattern was chosen such that it excited only one specific thermal mode and the first or lumped mode. Consequently, we have measured the behaviour of a chosen mode plus the first mode.

The thermal response was predicted by simulations on 1D and 2D models of the system as shown in Figure 1. Then, these measured and simulated responses were

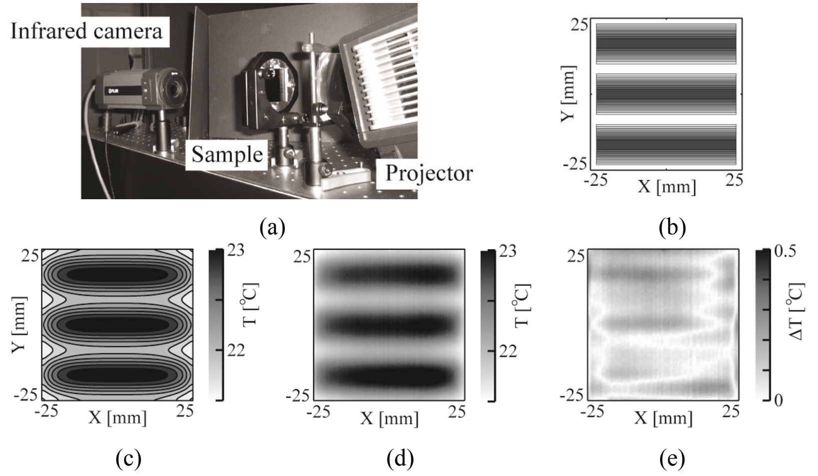
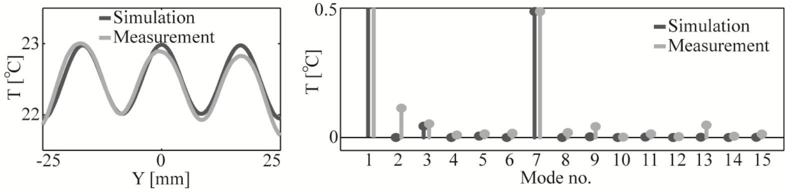


Figure 2: (a) Measurement set-up based on [4]. (b) Heat load profile for mode seven with a power of 0.5 Watt. (c) Simulated temperature response after 63 s. (d) Measured temperature response after 63 s. (e) Temperature difference between the measured and simulated response.



(a) (b)

Figure 3: (a) The temperature responses in 1D after 63 s. (b) The modal amplitudes of the temperature responses of Figure 3(a).

decomposed into contributions associated to the thermal modes of the numerical models. Accordingly, the transient behaviour of these contributions was compared.

3 Results

In this paper we only present the results of the measurements regarding the excitation of the third symmetric or seventh thermal mode (see Figure 1 and 2(b)), whereas the measurements for the other modes gave similar results. The measured and simulated temperature response (see Figure 2(c) and 2(d)) are in good agreement as shown in Figure 2(e) and 3(a). In addition, Figure 3(a) suggests the difference to be partly misalignment and scaling.

The decomposition of the 1D transient response into the modal contributions result, as expected, in two peaks for both simulated and experimental responses (see Figure 3(b) and 4): the first or lumped and seventh mode. The transient responses of these important modes are well predicted by the simulations. The difference between the modal contributions of the simulated and measured response is seen at the second mode and the residue, due to measurement noise.

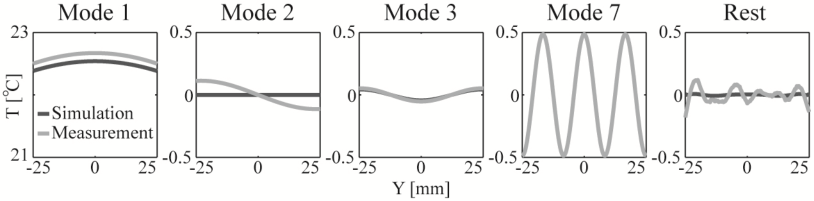


Figure 4: The simulated and measured modal contributions of the temperature responses presented in Figure 3(a).

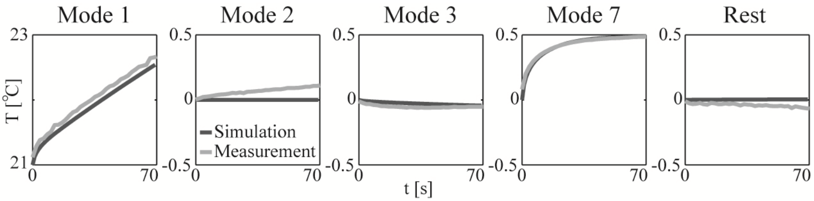


Figure 5: The transient responses of the simulated and measured modal amplitudes.

4 Conclusion

Several load cases were studied such that each load excites only one thermal mode. The numerical simulations correspond well with the measured responses. In addition, the transient response of the measured modal contributions is well predicted. Thus, we can excite and measure a specific thermal mode of which we know the transient and spatial behaviour. Consequently, the response to an arbitrary and time varying load can be separated and predicted. Hence, this concept of the thermal modal analysis can provide a reduced thermomechanical model as well as a basis for design optimization and compensation strategies of the precision devices.

Acknowledgement:

Pieken in de Delta, Provincie Noord-Brabant and Samenwerkingsverband Regio Eindhoven should be acknowledged for their support in this project.

References:

[1] Li, J. et al. (2009) *Thermal-error modeling for complex physical systems: the state-of-arts review.* Int. J. Advanced Manufacturing Technology, 42 (6): pp. 168 – 179.

[2] Weck, M. et al. (1995) *Reduction and Compensation of Thermal Errors in Machine Tools*. CIRP Ann., 44 (2): pp. 589 – 598.

[3] Shih, T. and Skladany (1983) *An Eigenvalue Method for Solving Transient Heat Conduction Problems*. Int. J. Numerical Heat Transfer, Part B: Fundamentals, 6 (4): pp. 409 – 422.

[4] Saathof, R. et al. (2011) *Evolving research on a non-contact adaptive optic actuation method for wavefront correction*. In Proc. 11th EUSPEN International Conference.