Thermal effects

In precision engineering, thermal effects have always been important in reaching high precision. Yet, over the years little attention has been given to this subject. Therefore, Mikrocentrum, in cooperation with Tegema Group, decided to organise a second seminar on thermomechanics, following the first one held four years ago, which attracted considerable interest. This year, the seminar focused on the control of thermal behaviour of precision systems. Once again, attendance was above average, underlining the topicality and relevance of this issue.

• *Ronald Lamers* •

In precision systems, thermal effects have a large influence on the desired accuracy and throughput, especially when these systems have to perform under extreme thermal conditions (for example, vacuum or cryogenic). Therefore, it is very important to give this aspect sufficient attention in the design phase. Examples are machine tools that are crossing the submicron boundary for machining accuracy, and measurement machines that can reach accuracies in the order of nanometers. Printing systems often work with fluid temperatures above 100°C and position accuracies of micrometers over a large range. The chosen system concept in most of these cases is strongly cost-driven.

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Figure 1. Impression of the information market that was part of the seminar.

Control of thermal behaviour

Wafer steppers, electron microscopes and space instrumentation can only function properly if the thermal stability is guaranteed in the order of nano- or even picometers. The seminar looked more closely at the control of thermal behaviour of precision systems. Topics included design principles such as the thermal centre, the right

in precision systems

choice of material, passive or active temperature conditioning and the compensation of thermomechanical deformations. Furthermore, attention was given to the modelling and analysis of thermomechanical systems during the design phase and to performing measurements during the test phase.

An historical overview

Theo Ruijl, concerned with thermal effects in engineering within FEI Company, acted as the chairman of the day. In his introduction, he gave an historical overview, going back as far as 1600. Marine chronometers were one of the first precision systems for which thermal aspects were considered: the differences in thermal expansion of materials were used to neutralise thermal effects. The period 1800-1900 showed some achievements in early precision manufacturing and metrology.

Recent examples are ultra-precision diamond turning, where subnanometer surface finishes and submicron form accuracies are achieved. Current opinion on the international status of thermal error research is best described by citing James Bryan from his 1990 paper [1]: '*…In spite of some excellent research…thermal effects are still the largest single source of dimensional errors and apparent non-repeatability of equipment*'. Furthermore, it can be observed that thermal effects are everywhere in all relevant market areas of Dutch precision engineering, such as precision manufacturing and the semiconductor, space, automotive, medical, pharmacy, printing and energy industries.

Large-format inkjet printers

A presentation of the thermal aspects in large format inkjet printers was given by Jos Gunsing of NTS Mechatronics. Positioning errors of the ink droplet can severely disturb the printed image, which may cause banding and colour shifts. The subject of the presentation was the Agfa M-Press Tiger Inkjet Printer, which has a print format of 2.6 x 1.6 m^2; see Figure 2. The system consists of 64 print heads, and the printing motion and substrate handling functions are separated. The overall dot positioning accuracy is 20 µm, the motion errors are smaller than 8 µm and the overlay is 50-100 µm. The main heat sources are the print heads (max. 30 W each), UV sources and the linear motors. In order to achieve the desired accuracies, the temperature conditioning of the system needed to be better than ±0.1°C during one print cycle and ±1°C over longer periods. The accuracy is reached by applying design principles, thermal conditioning techniques such as water cooling and software compensation. Thermal effects were a substantial part of the design effort and thermal lumped-mass modelling gave results that could be used quite well. However, one of the major challenges for future generation printers will continue to be thermal stability.

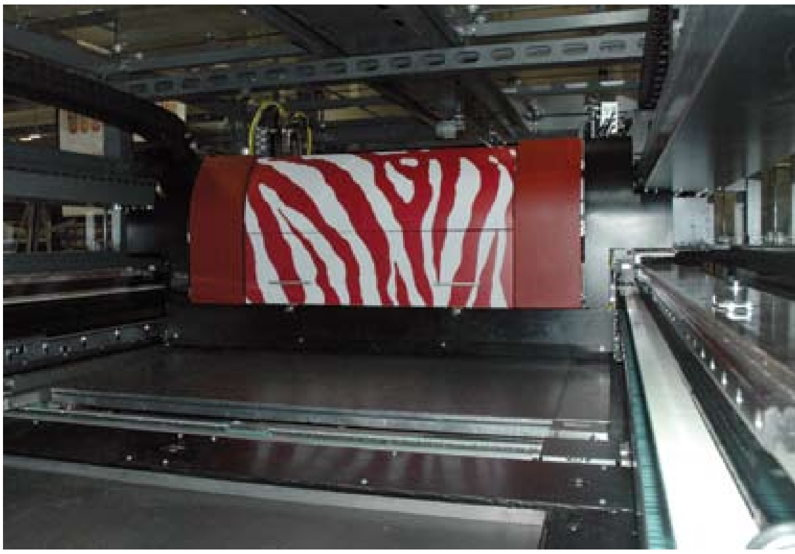

Figure 2. The large-format Agfa M-Press Tiger Inkjet Printer.

FEM simulations

Willem Dijkstra of Mecal gave a presentation on the use of FEM simulations (Finite Element Method). His topic was the effect on overlay as a result of 'wafer heating' in wafer steppers. The total allowable error for the production of chips with features of 45 nm is 15 nm. Approximately 1 nm of this budget is allocated for thermomechanical effects. Heat dissipation during the lithographic production of chips can lead to errors. A wafer is divided into fields that are exposed several times one after another. 95% of the light is transformed into heat and absorbed in the wafer. Due to this absorption, the wafer, and the table and chuck holding the wafer, heat up and deform due to thermal expansion. The mirrors on the chuck, which are used for interferometric position control, also deform. Optimisation was realised by using an FEM model and a good understanding of the thermal interactions between wafer, table and chuck. This complex, large model was kept manageable by the use of submodels of certain complex interactions (for example, thermal contact properties) within the system. Dijkstra underlined that FEM simulations are a tool, and not a goal. A design optimisation can only be realised by understanding the real physics.

Tuning thermal constants

Rens Henselmans of TNO presented the thermomechanical design of an Optical Tube Assembly (OTA). The ESO (European Southern Observatory) is expanding one of its Very Large Telescopes in Paranal (Chile) with the ‘4 Laser Guide Star System’, which creates artificial stars to serve as a reference for their adaptive optics systems. Air turbulence causes blurring of the stellar light, which is arriving as a perfect wave front at the earth’s atmosphere. Mirrors can be deformed to correct these turbulence errors. To that end, a ‘reference star’ is created. A 25 W laser (Continuous Wave, 589 nm) projects its beam into the sky, where it excites sodium atoms in the atmosphere between 90 and 100 km high, which in turn start emitting light.

Figure 3. The Optical Tube Assembly expands a 15 mm input laser beam to a steerable 300 mm output beam.

The OTA expands a 15 mm input beam to a steerable 300 mm output beam with strict wave front requirements (50 nm rms wave front quality); see Figure 3. The beam expander should not defocus over 8 hours as a function of the ambient air temperature (0-15 °C; -0.7 °C/hr gradient). The design was therefore passively athermalised in the steady state as well as the transient state by tuning the thermal time constants of the different components, and by matching the expansion coefficient of the structure to the varying properties of the lenses. Different materials were used to gain suitable compensation coefficients. Because steady-state as well as transient behaviour has to be considered, both static and dynamic properties are important aspects of the design solution.

Cheap and reliable micrometers

For printer manufacturer Océ, it all comes down to cheap and reliable micrometers. Rob van Loon presented some of the thermomechanical effects in Océ’s new Colorwave 600 colour printer. He underlined that thermal effects are often the largest disturbance and are often very complex. It is important to map out the sources and the effects, both steady state and transient. Within the Colorwave 600, design principles have been applied to gain reproducible behaviour, since the system’s error is its sensitivity multiplied by the disturbance. By minimising the sensitivity, the error is also minimised. Correction by means of temperature measurements is also applied. Temperature gradients, which cause bending deformations, are minimised by choosing a material with a low α/λ ratio (for example, aluminum), where α is the coefficient of thermal expansion and λ is the thermal conductivity. One major issue is paper buckling during paper transport, which is caused by thermal, hygroscopic (for example, climate) and mechanical interaction. This subject is still under investigation.

Heat transfer visualisation

Flow visualisation is often used as a technique to gain insight into fluid flows, for example in the aerodynamic design of vehicle bodies, weather predictions, and optimisation of mixing processes. Michel Speetjens of Eindhoven University of Technology showed that heat transfer can be made visible in a comparable way, which allows for thermal analysis with well-known flow visualisation methods. In his presentation, he demonstrated the mathematical equivalent of fluid motion and heat transfer. Some very illustrative 2D and 3D examples where given, for instance for heat transfer in fluids with high and low Péclet number Pe (~ convection / conduction). The vivid discussions afterwards showed that the subject was interesting and this new technique will offer new perspectives.

Thermal drift measurement

Besides design and analysis, measurements on precision systems for validation are also very important. Guido Florussen of IBS Precision Engineering presented some aspects of performing measurements on the spindle of machine tools. Typical heat sources in machine tools are linear drives, motors, spindle drives, hydraulic pumps, gear transmissions, bearings, electronics and, last but not least,

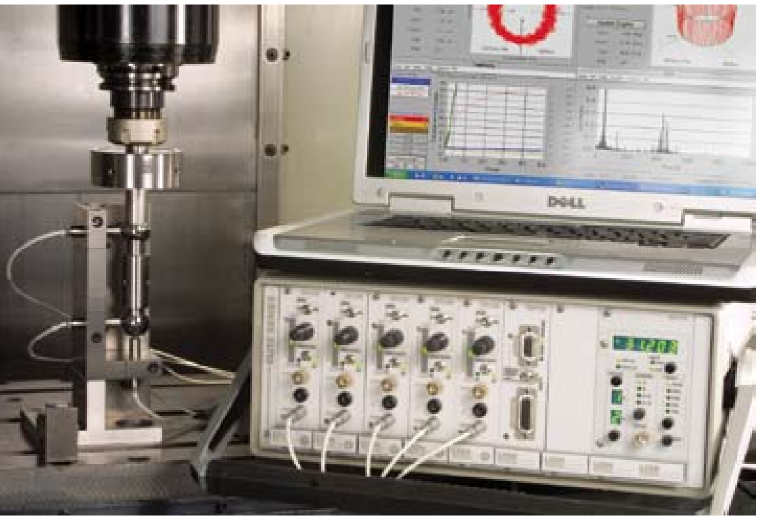

Figure 4. Double-ball set-up for IBS's Spindle Error Analyser.

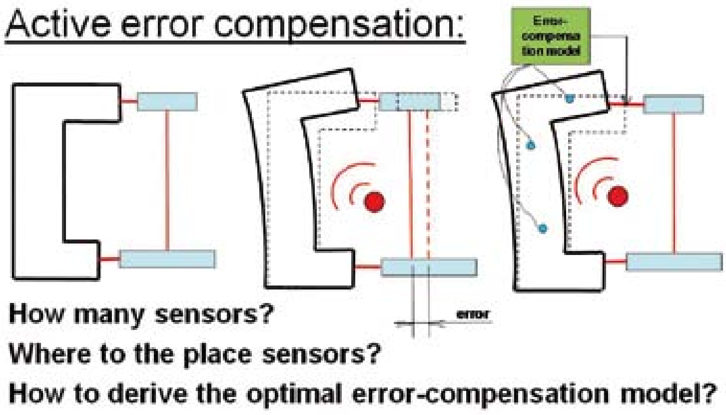

Figure 5. Schematic of a thermomechanical compensation model for position control.

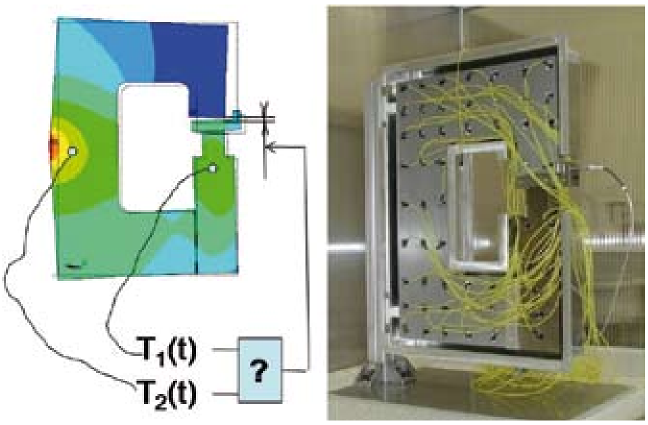

Figure 6. Optimisation of the location of temperature sensors.

the environment. The effects of these heat sources on the expansion of the spindle can be measured with a so-called Spindle Error Analyser. With this method, a very accurate (single) ball is placed inside the spindle, the machine is started and the x, y and z displacement of the ball is measured accurately with three capacitive sensors. With a double ball, see Figure 4, it is possible to also measure Rx and Ry rotations. Some specific measurement results where presented, which clearly show whether a machine is (not) compensated for thermal expansion. Compensation can be realised by active closed-loop cooling techniques or by software compensation. Florussen also mentioned some do's and don'ts regarding these types of measurements.

Model reduction techniques

Marco Koevoets of Philips Applied Technologies discussed thermomechanical compensation models for position control; see Figure 5. Model reduction techniques such as modal analysis, Arnoldi and proper orthogonal decomposition can be used to determine the thermal state of a system based upon measured temperatures. The selection of the right model reduction technique depends on the pre-knowledge of the corresponding system: for example, are the loads known?

With knowledge of the thermomechanical behaviour of the system, the corresponding time-varying thermal deformations can be calculated real-time and compensated for. The performance gained depends on the uncertainty of the thermomechanical model, the configuration of the temperature sensors and the uncertainties in the temperature measurements. With the use of these techniques, the location of the temperature sensors can be optimised; see Figure 6.

Conclusion

The seminar topics covered an interesting and diverse range of aspects, from design and analysis to measurements. The diversity in the attendance showed that thermal effects are relevant to many different applications. The issue will remain hot, as evidenced, for example, by a forthcoming special issue of the Mechatronics journal. See the call for papers on page 57.

Reference

[1] Bryan, J.B., 1990, "International Status of Thermal Error Research". CIRP Annals, Vol. 39/2.

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