When precision cannot stand the heat

In precision systems, thermal effects have a large influence on system performance, regarding accuracy and throughput, especially under extreme conditions (for example, vacuum or cryogenic). Therefore, it is crucial to give this aspect sufficient attention in the design phase. This article focuses on the control of thermal behaviour of precision systems. Topics include the proper choice of materials, design principles, passive or active temperature conditioning and the compensation of thermal deformations.

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From its invention in 1656 by Dutchman Christiaan Huygens until the 1930s, the pendulum clock, as shown in Figure 1, was the world's most precise timekeeper. It uses a pendulum, a swinging weight, as its timekeeping element. Huygens was inspired by investigations of pendulums by Galileo Galilei beginning around 1602. Galileo discovered the key property that makes pendulums useful timekeepers: isochronism. It means that for small swings the period of swing of a pendulum is approximately constant. Successive swings of the pendulum, even if changing in amplitude, take the same amount of time. The introduction of the pendulum, the first harmonic oscillator used in timekeeping, increased the accuracy of clocks enormously, from about 15 minutes per day to 15 seconds per day.

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The period of swing of a simple gravity pendulum depends on its length, the acceleration of gravity, and to a small extent on the amplitude of the swing. It is independent of the mass of the bob. If the amplitude is limited to small swings, the period T of a simple pendulum, the time taken for a complete cycle, equals $2\pi\sqrt{(L/g)}$, where L is the length of the pendulum and g is the local acceleration of gravity.

The largest source of error in early pendulums was associated with slight changes in length due to thermal expansion and contraction of the pendulum rod with changing ambient temperature. This was discovered when people noticed that pendulum clocks ran slower in summer, by as

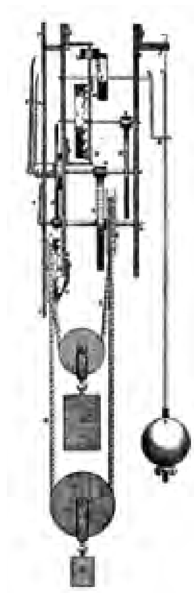


Figure 1. Huygens' pendulum clock. (Source: Wikipedia)

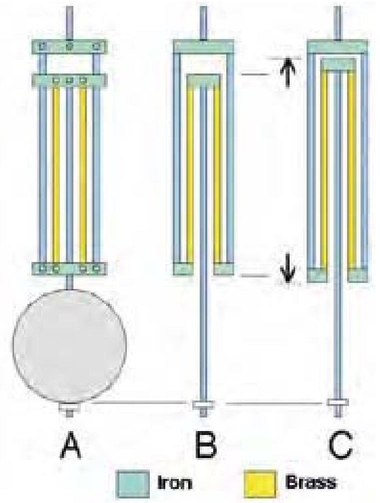


Figure 2. Harrison's gridiron pendulum clock. (Source: Wikipedia)

much as a minute per week. A pendulum with a steel rod will expand by about 11.3 parts per million with each degree Celsius increase (ppm/°C), causing it to lose about 0.5 seconds per day per degree of temperature change.

The most widely used compensated pendulum was the gridiron pendulum, shown in Figure 2, invented in 1726 by British clockmaker John Harrison. The gridiron pendulum did not change in length with temperature, so that its period of swing stayed constant when ambient temperature changed. It consists of alternating brass and iron rods, assembled in such a way that the effects of their different thermal sensitivities cancel each other.

Around 1900, low-thermal-expansion materials were developed and used as pendulum rods, which made elaborate temperature compensation unnecessary. In 1896, Charles Édouard Guillaume invented the nickel steel alloy Invar. Invar has a coefficient of thermal expansion (*CTE*) of around 1.2 ppm/°C, resulting in pendulum temperature errors of about 0.05 seconds per day. This residual error could be compensated to zero with a few centimetres of aluminium under the pendulum bob, compensating the expansion of the Invar rod. Later, fused silica was used, which had an even lower *CTE* (0.55 ppm/°C).

Thermo-mechanical design

The use of low-*CTE* construction materials and design principles such as the gridiron pendulum are still common practice in precision engineering. Invar is still used as construction material in some of the most advanced machines. Modern construction materials include Zerodur (*CTE* ~ 0.02 ppm/°C) and silicon carbide; see Figure 3.

In general, thermal problems in precision engineering are related to the expansion and contraction of materials as a result of internal (actuators, electronics, cooling water, etc.) or external heat sources/sinks (environment, people, processes, etc.). To avoid these problems, it is best to locate the heat sources away from the critical components. In most cases, this is not possible, so one has to deal with the effects of thermal disturbances.

When tackling thermal effects, three main steps can be defined:

- Material selection and geometry.
- Thermal conditioning.
- (Software) compensation.

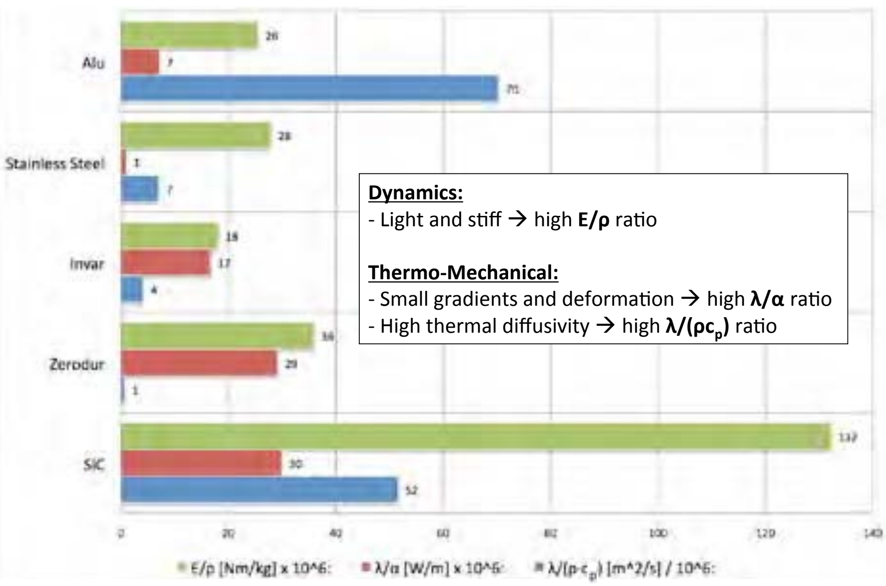


Figure 3. Material properties of some typical construction materials.

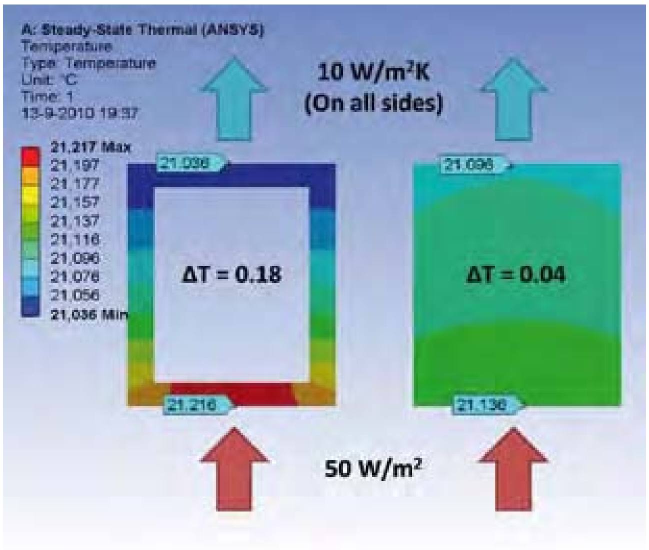


Figure 4. Cross sections: gradient reduction ~ factor 4.

Figure 5. GAIA test set-up built by TNO Science and Industry.

Besides the above mentioned aspects, also predictive modelling and thermal measurements are important topics to discuss. However, these are not covered in this article.

Material selection

The choice for materials with a low coefficient of thermal expansion (*CTE*) α is often proposed when dealing with thermal effects. Bending deformations caused by temperature gradients are often more significant than homogeneous expansion (or contraction). This means that not only the *CTE* is important, but also the thermal conductivity λ. The higher the thermal conductivity, the smaller the temperature gradients and thus the bending deformation. In order for a structure to be insensitive to spatial temperature gradients, a material with a high λ/α ratio must be selected.

When dealing with dynamic thermal disturbances, the thermal capacity also becomes important. The material properties that determine the thermal capacity are the density ρ and the specific heat c_p. Different components in a structure, e.g. a metrology loop, will have different thermal capacities. Changes in temperature will cause dimensional changes of all components in the loop (errors). The components will react differently, unless they all cancel out around the metrology loop, which is unlikely in any situation involving dynamic temperature variations.

Besides the thermal capacity, the thermal diffusivity is an important material property as well. The thermal diffusivity is defined as $\lambda/(\rho c_p)$. A high thermal diffusivity means that a transient heat distortion is quickly spread out to a uniform temperature distribution. The sensitivity to thermal gradients and the thermal diffusivity can be combined to the characteristic $\lambda/(\alpha\rho c_p)$, which expresses the capability of a material to maintain its shape due to temporal and spatial temperature variations. Material properties for some (typical) construction materials are shown in Figure 3.

From this outline, it is clear that when dealing with thermal effects, not only the *CTE* is important, but also λ, ρ and c_p. When dealing with thermal stresses, also the Young's modulus E becomes important. This complicates material selection for thermal stability, compared to e.g. dynamics (vibration), where in most cases one only strives for a material with a high E/ρ ratio (specific stiffness).

Geometry

An important design philosophy within precision engineering is concerned with design principles for precision. One of the pillars of this design philosophy is design for stiffness. The intention is to design a structure, for instance a frame, in such a way that the (mechanical) natural frequency is maximised in order to achieve maximum positional accuracy. The definition of the natural frequency is the square root of the stiffness c divided by the mass m, $\sqrt{(c/m)}$. When striving for a construction with a high natural frequency, one aims to maximise stiffness and minimise mass. This often leads to box-like constructions made out of sheet metal.

From a thermal point of view, one often wants to maximise conduction through a structure so that a transient thermal disturbance is quickly spread out to a uniform temperature distribution, limiting thermal gradients and thus bending deformations. In that case, structures with solid cross sections are preferred over box-like constructions. After all, metal still conducts heat a lot better than air. However, by using sheet metal constructions, the opposite is achieved, as illustrated in Figure 4.

In Figure 5, a test set-up is shown for the optical system of the GAIA satellite [1]. The set-up was built on a large aluminium base plate. The optical path can be designed such that it is insensitive for homogeneous expansion. Only bending deformations disturb the optical path. The high thermal conductivity of aluminium minimises temperature gradients and thus bending deformations. The total mass of

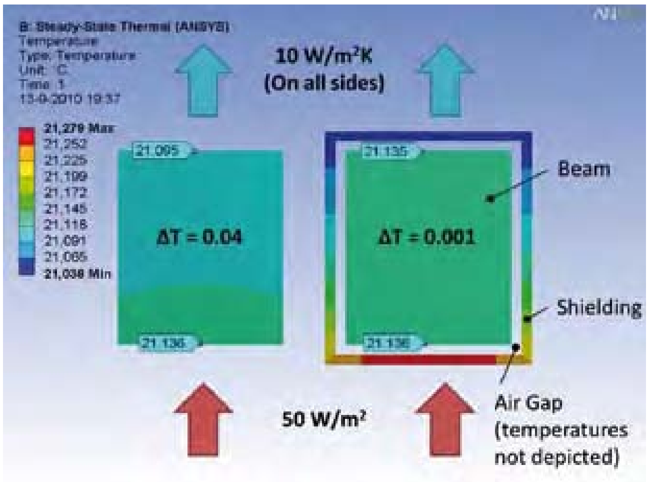


Figure 6. On the right, the beam is enclosed by thermal shielding: gradient reduction ~ factor 40.

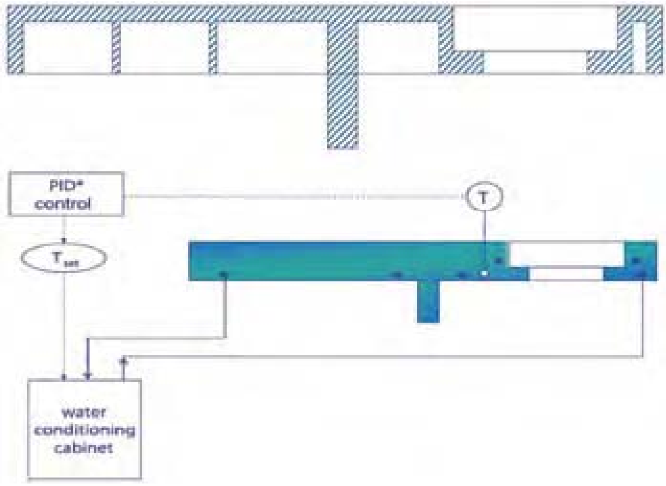


Figure 7. Traditional Invar sheet-metal metrology frame versus solid aluminium metrology frame.

the test set-up is 335 kg. Because of this high thermal capacity temperature changes can only develop slowly.

Thermal contact resistances between different components can also have a strong effect on the thermal behaviour of a structure, but are not further discussed here. If the selection of the right material and the application of the proper geometry do not result in the desired system performance, the next option is thermal conditioning of the construction. This can be done passively or actively.

Passive thermal conditioning

The most popular passive technique is applying thermal insulation to reduce the rate of conductive heat transfer. In order to shield a structure from thermal radiation, it is possible to apply a coating with a low emissivity ε, reducing both absorption and emission. In reverse, absorption and emission can be increased by applying a high emissivity.

In [2] a metrology frame is described that is enclosed in an aluminium box, which due to its thermal capacity acts as a low-pass filter for dynamic thermal disturbances such as operators and environmental fluctuations. The high conductivity of aluminium creates a uniform temperature distribution over the shield, thereby also creating a uniform heat load on the metrology frame inside and thus reducing thermal gradients in the frame; see Figure 6. Other techniques include creating a mini-environment, using IR-shields and applying large thermal masses, as illustrated in the GAIA satellite test set-up.

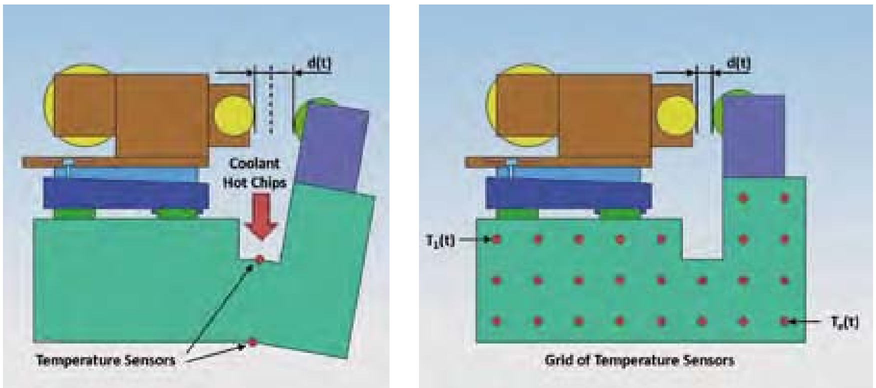
Active thermal conditioning

The most popular active technique is cooling, which can be for instance water, oil or air cooling. This can be done ‘open loop’ or ‘closed loop’. Besides using channels, it is also possible to apply showers for thermal conditioning of a structure. As described in [3], a metrology frame made out of Invar plates, which was used for an ASML wafer stepper, was replaced by an solid aluminium frame with closed-loop water cooling; see Figure 7). Because of the thermal properties of aluminium, active water conditioning is highly effective. The internal conduction is high enough to enable excellent conditioning of the entire frame. The relatively large heat capacity of aluminium ensures that temperature fluctuations, of the environment as well as the cooling water, are dampened very well. Next to the above mentioned advantages, this solution yields significant reductions of cost price and lead production time.

Besides conditioning techniques involving gases or liquids, it is also possible to apply thermal actuators. A simple example is placing a heating element next to a drive system. When the drive system is powered, heat will be dissipated. By applying a control loop, the heating element guarantees that always the same amount of heat will be dissipated, even when the driving system dissipates less or no power. In this case, heat dissipation remains constant and the structure will reach a thermal steady state, so that thermal stability is achieved.

Compensation

If the right choice of material and geometry and the proper application of conditioning techniques do not lead to the desired system performance, the last option is to apply compensation techniques. If the dominant thermal deformation can be identified, it may be possible to compensate for this deformation using the machine controls (software). This is illustrated in Figure 8a [4], which shows a machine tool. When machining a workpiece, hot chips and cooling fluids are washing down on the machine base; causing it to deform (bending). This deformation leads to an error (displacement) between



a b

Figure 8. Thermal compensation using temperature sensors.
(a) A simple sensor configuration.
(b) A sensor grid.

cutting tool and workpiece. Temperature sensors are placed at the bottom and top of the machine base. The thermal deformation of the machine base can be predicted by determining the relation (sensitivity *S*) between the measured temperatures (T_{top} and T_{bottom}) and the thermal deformation *d*.

$$d = S(T_{top} - T_{bottom})$$

The sensitivity can be determined analytically (modelling) or empirically (measuring). By applying a software correction, based on this relation and the measured temperatures, the control system of the machine tool can compensate for the thermally induced deformation.

It is not always easy to determine the dominant thermal disturbance or deformation in a machine tool. In many cases, several dominant heat sources are present that influence the thermal stability, such as the drive systems and the environment. In that case, a grid of temperature sensors can be placed on the machine base, as illustrated in Figure 8b. The relation between the measured temperatures and the thermal deformation of a certain point of interest, for instance between the cutting tool and the workpiece, can be expressed in matrix form as:

$$d = [s_1 \quad \cdots \quad s_n] \begin{bmatrix} T_1 \\ \vdots \\ T_n \end{bmatrix}$$

Determination of the sensitivity vector can be accomplished by placing a local heat source on each temperature sensor location in turn. In that case, *n* different temperature distributions and *n* different deformations (at the point of interest) are measured. The sensitivity vector can be determined by the relation:

$$[s_1 \quad \cdots \quad s_n] = [d_1 \quad \cdots \quad d_n] \begin{bmatrix} T_{1,1} & \cdots & T_{1,n} \\ \vdots & & \vdots \\ T_{n,1} & \cdots & T_{n,n} \end{bmatrix}^{-1}$$

Also in this case, the sensitivity vector can be determined either analytically or empirically, or in combination. The number of temperature sensors can be reduced by removing those sensors with the smallest sensitivity [2]. Compensation techniques are more and more applied in precision machines, especially in machine tools and measuring machines. The aforementioned techniques are simple examples. More advanced techniques are being developed, such as thermal system identification (e.g. thermal mode shapes). These techniques are explained in more detail in [5].

Conclusion

Three basic steps have been defined to tackle thermal effects in precision systems. These steps are the selection of the proper construction material in combination with the right choice of geometry, the application of passive and active thermal conditioning techniques and software compensation. A brief outline of these three steps has been given, but important subjects such as modelling and measuring have not been discussed.

Thermal effects in precision systems are becoming more and more important. The subject is still under development and not much knowledge is available in textbooks. Therefore, it would be appreciated by many if engineers would share their knowledge on the subject, e.g. in a professional journal like Mikroniek.

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