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Strategies for Thermal Error Modelling and Design Mitigation

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Abstract
Ever since John Harrison addressed the longitude problem, thermal errors remain the most subtle and worrisome encountered when navigating the ocean of errors that affect devices from precision machines and instruments to battery powered systems, giant machines, and civil engineering structures. Sources, sinks, resistances, masses, and phase changes (when appropriate) must be accounted for and managed in the presence of great uncertainty of heat transfer conditions most notably convection and radiation, but also variance in conduction across surfaces. Deterministic design strategies, from kinematic to elastic averaged systems can be important elements in the precision design toolbox. Examples include the use of symmetry in 3D printing machines, kinematic segmented structures, and elastic averaged probe card systems.

Thermal errors, kinematic, elastic average, design strategy

1. Introduction

Thermal errors are cumulative and in the absence of steady state operation of the machine, in time, motion, and power consumption, they often appear to be non-repeatable. If the duration of part manufacture is significantly less than the time constant of warm-up, a workable operational strategy is measure parts as they are created and then in real time adjust tool offsets to compensate for thermal errors in the machine. In the ultimate limit, a digital twin of the machine would be updated in real time with many temperature readings, and a few careful distance measurements between points, to create fast tool path offset updates. The future of machine design should inevitably become more deterministic so the design process yields an accurate digital twin that can serve as a thermal error compensation model. With this in mind, design strategies for helping digital twin and machine robustness are ever more important.

2. Design Strategies

Design strategies for thermal error mitigation can help in the short term with conventional machines and also for longer term digital twin-based designs. A taxonomy of strategies must include consideration of energy sources, sinks, and transmission paths as well as the kinematics of the machine as elements' lengths and temperatures change. Harrison was the first precision design engineer to apparently have mastered these issues in a complex mechanism: a clock that solved the longitude problem [1] and this landmark achievement showing the task could be done has served as a great motivator ever since. Since then, much progress has been made to formally represent the issues so they can be systematically addressed. Bryan [2, 3] represented these issues graphically and here we consider some of the specific design strategies to address them.

2.1. Thermocentric Design

Thermocentric design seeks to balance the expansion of an element on one direction with the expansion of an element in another. Perhaps the best-known example is that of back-to-back bearing configurations. A rotating haft often gets hotter than the housing. Rolling element bearings can thus be arranged such that their contact angles diverge so radial expansion of the shaft (relative to the housing) while increasing load on the rolling elements, is offset by axial expansion that decreases the load on the rolling elements [4].

Another well-known example is a preloaded ballscrew, where the screw is stretched and as it warms up, mechanical strain is replaced with thermal strain with the net result being the lead remains constant. While straightforward, the devil is in the details: The thermal expansion of an element is geometrically governed by the length dimension in the direction of interest. However, the axial stiffness of a ballscrew is characterized by the diameter squared / length, and the stiffness of the ballscrew bearing supports is non-linear Hertzian so the challenge of thermometric design increases as the desired overall stiffness of the machine increases. But when the screw is stretched by turning a nut that reacts against the support bearings, as the ballscrew is pre-stretched, the load of the support bearings increases which causes them to generate more heat when they rotate.

Another example is maintain axial length of a member, a preload bolt for example, through the use of sleeve elements with different expansion coefficients in accordance with the lengths of the elements [5].

A variation on this is avoiding bimetallic effects which are commonly experienced when steel profile rail bearing rails are bolted to one side of modular aluminium frame structures, as is popular with low-cost machines. When these machines operate at a temperature very different from that at which they were assembled, substantial predictable warping can occur. Table 1 is the output of a spreadsheet that shows typical values that may be encountered.

BiMat.xls		
Determine thermal errors in a bi-material beam		
Written by Alex Slocum. Last modified 2020.10.11 by AS		
Enter numbers in **BLACK** outputs in **RED**		
Be consistent with units		
Beam and environment	**Units**	**Value**
Length of beam: L	m	**2**
Change in temperature: DT	C	**4.0**
Cross section 1 (e.g., bearing rails) properties		
Material		**Steel**
Modulus of Elasticity: E_1	N/m^2	**2.00E+05**
Coefficient of thermal expansion: alpha_1	1/C	**1.20E-05**
Bearing rails (enter YES or NO)		**YES**
Number, Nrails		**2**
Width, wrail	m	**0.015**
Height, hrail	m	**0.015**
TOTAL (e.g., if 2 bearing rails) Moment of inertia, I_1ue	m^4	**0**
TOTAL (e.g., if 2 bearing rails) Cross section area, A_1ue	m^2	**0.00045**
Moment of inertia: I1	m^4	**0**
Area: Ar1	m^2	**0.00045**
Cross section 2 (structure) properties		
Material		**Aluminum**
Modulus of Elasticity: E_2	N/m^2	**6.67E+04**
Coefficient of thermal expansion: alpha_2		**2.40E-05**
TOTAL flange thickness (top + bottom) (0 for rect. beam): ft_2	m	**0.012**
Height: h_2	m	**0.1**
Width: b_2	m	**0.1**
TOTAL web thickness (left + right) (bi=bo for rect. beam): wt_2	m	**0.012**
Moment of inertia: I_2	m^4	**0**
Area: A_2	m^2	**0**
Results		
Max. displacement error (middle of simply supported beam)	m	**-5.19E-06**
Max. slope error (end of simply supported beam)	radians	**-1.54E-06**

Table 1. Spreadsheet to predict warping of aluminium frame member by linear motion guide rails bolted to one side.

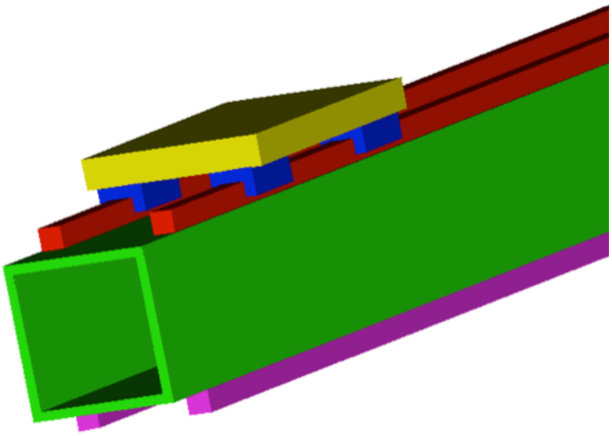

Figure 1. Balanced design where steel bars of same size as bearing rails are bolted on opposite side of aluminium frame member.

To mitigate the issue, steel bars of the same cross section can be bolted to the opposite of the beam, as Illustrated in Figure 1, or two rails mounted on opposite sides of the beam along the neutral axis can be used.

2.2. Isolation and shielding

In view of energy sources or sinks, structures absorb or adiate heat and thus simple radiation shields with appropriate ventilation or insulation between if possible, can help greatly. Cylindrical radiation shields around lens barrels or microscope bodies is a fine example [6]. For machine tools, which often use flood coolant to wash away hot chips, a common cost saving measure/big mistake, is to form the collection gutters directly into the frame casting, where the warm high velocity cutting fluid transfers heat to the frame. A simple sheet metal gutter separated from the frame is a low-cost effective strategy. Similarly, on large machines, evaporative cooling effects can be mitigated with simple sliding covers. Radiation shields' effectiveness increases as they are added in series, and a fine contemporary example is the sunshield on the James Webb telescope [7].

Within a machine itself, sources can be isolated from the structure by thermal insulating mounts, and these can be kinematic to facilitate rapid precise assembly. The use of high local radius of curvature kinematic couplings ("canoe" balls in vee grooves) enables isolation with kinematic alignment and very high stiffness [6]. The six Hertz contact regions represent a reduction in surface contact area by several orders of magnitude, while stiffness does not have to be too adversely affected.

Spindles and Servomotors are one of the biggest heat sources in precision machines and they require precise alignment. Spindles have been mounted in various ways to maintain centre location, such as by using "wings" and flexures. Servomotors must be aligned with the shafts they control, such as a ballscrew, as torsionally stiff servo couplings can only withstand so much misalignment. Typically, a precise round flange centres the motor in a bore on the structure, and then four bolts in corner clearance holes press the motor flange firmly to the structure. This achieves good stiffness but unfortunately also good heat transfer. It is suggested here that this could be an effective new standard for motor mounting: kinematic vee grooves in a motor mounting flange to facilitate isolation mounting while enabling high torque transmission and stiffness. Note that a similar design for lower cost would be to modify the traditional four bolt holes in the corners of the motor mounting flange with four slots to yield an effective split groove kinematic coupling type slot mount [8]. Stainless steel (which has poor conductivity) or ceramic spacer standoffs thermally isolate the motor, and same diameter should screws then locate the motor axis with respect to the bore in the structure as shown conceptually in Figures 2 and 3.

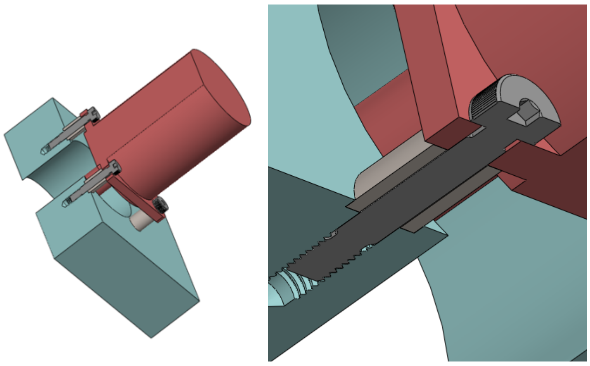

Figure 2. Split groove kinematic slot coupling with insulating standoffs for servo motor mounting.

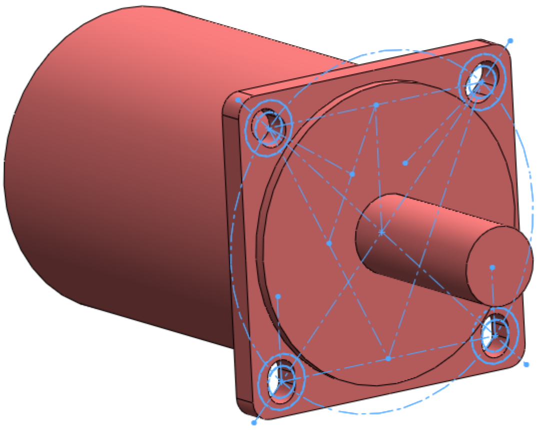

Figure 3. Proposed motor flange "standard" to use four slots instead of holes for split groove kinematic mounting to achieve axis alignment.

The "opposite" of the kinematic arrangement is an elastically averaged design, where a large circular array of slots aligned with the circle centre receive pins. When used to mount thin structures, such as circuit boards which may act as probe cards, the centre of the structure remains precisely fixed while the rest of the structure can grow radially [9]

3. Conclusions

Thermal errors can be addressed with deterministic design principles and good operations management. No amount of good design, however, can fully account for inadequate site operation such as allowing room temperatures to swing wildly. As digital twin technology develops for machine operation, it is recommended that the design calculations performed become part of the twin's design record such that developers of the twin and controls engineers can make best use of them to more accurately predict and control thermal error compensating tool offsets.

References

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