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Heat transfer strategies for temperature sensitive components in vacuum environments

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Abstract

This article discusses methods for overcoming thermal challenges in vacuum environments, so that a deliberate heat transfer strategy can be generated in the conceptual machine design phase. Vacuum environments, where convection is limited, and precision machines, where temperature and thermal deformation of both the tool as well as machine structure are critical, require unique design strategies for successful heat transfer. This article presents trade-offs and challenges in the design of conductive thermal shortcuts, which are needed when requirements of temperature, thermal deformation and positional stability conflict with the mechanical stiffness requirements of kinematic mounts and guides. Alternative gas conduction and convection heat transfer strategies are given for cases where interactions between tool part and structural loads are relevant. Radiative heat source and heat sink strategies are mentioned for systems where surface deformations and stability are relevant.

Heat Transfer, Vacuum Environments, Thermal Shortcut

1. Introduction

How one decides to globally 'route' heat in a system, as much as one can guide the process, depends upon whether the environment serves purely as a sink, or whether the environment also functions as a structural and or reference frame as well. For systems where the environment of a vacuum chamber serves also as a reference or is part of the structural loop, heat transferred from a tool (improving local tool deformation) to the environment can actually cause larger deformations of the tool due to frame expansion or shifting of reference systems. In such a case, a local heat absorption strategy is often preferred, with thermal shortcuts acting to minimize deformations and positional drift.

This paper first presents an overview of a typical component thermal circuit in a vacuum environment. Secondly, options for reducing positional drifts and deformation using a thermal shortcut method are shown. Next a modified isolator-shortcut variation is presented. Finally options for convective and radiative improvements are given.

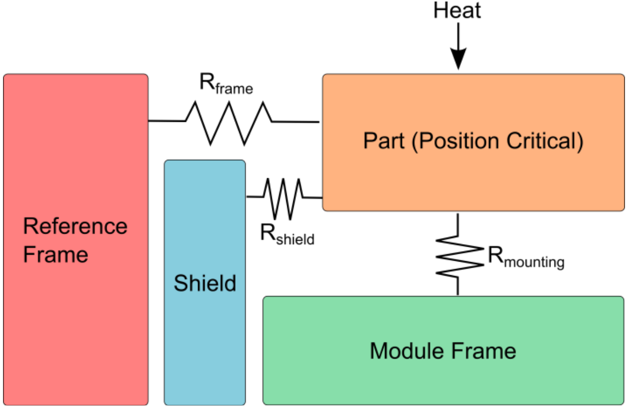

Figure 1. Typical machine layout of part with local heat absorption architecture.

2. Layout of a Machine Thermal Circuit

A typical scenario for a position critical part (tool tip, sensor head, or optical module) is shown in Figure 1. Here the part interacts with its local module frame with thermal resistance $R_{mounting}$ which usually includes mounting elements such as kinematics couplings, hexapods or flexural mounts. Given its short path and mechanical contact, this thermal resistance is usually the smallest and is often dominated by conduction. In vacuum systems, heat transfer to the outer reference frame or other structure occurs via radiation and gas conduction as represented by the thermal resistance R_{frame}. Although usually quite small, this heat path is often more critical than one would suspect because it affects positional stability and is more difficult to control in the design phase. Finally, thermal resistance to a local shielding element is shown as R_{shield}, and would also include radiative and gas conduction type effects. In total, a very simplified total thermal resistance is:

$$R_{total} = \left(\frac{1}{R_{mounting}} + \frac{1}{R_{frame}} + \frac{1}{R_{shield}}\right)^{-1} \qquad \text{Eq. 1}$$

where the resulting temperature increase of the part related to input heat load, Q_{source} is:

$$dT = Q_{source} R_{total} \qquad \text{Eq. 2}$$

and where individual heat loads to the resistance frame and shield are:

$$Q_{source} = Q_{mounting} + Q_{frame} + Q_{shield} \qquad \text{Eq. 3}$$

How to approach heat transfer options for this very simple case are shown next.

2. Conduction and Thermal Shortcuts

In order to limit thermal effects, one may consider lowering the mounting resistance. Two options for achieving this are presented using standard mounting and thermal shortcuts. However these standard options can in some cases be counterproductive to the design goal, in which case a stacked resistance concept is shown.

2.1. Standard Low Mounting Resistance Design

In the simplest case, to lower part temperature, one should lower the mounting resistance. It follows from Eq. 1 that lowering $R_{mounting}$ lowers the R_{total}, and with Eq. 2, dT. Such a method is used if a component or coating has a temperature limit. For a standard mount, such as in Figure 2, this involves material selection (higher thermal conductivity and combined merit functions), as well as adjustments to mount geometry.

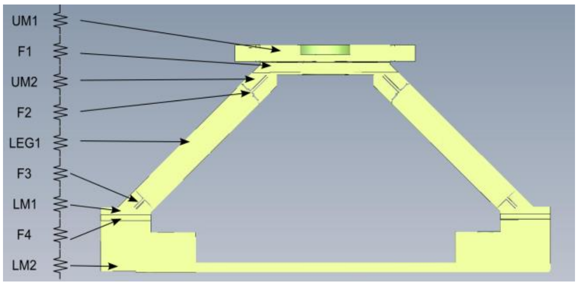

Figure 2. Kinematic mount $R_{mounting}$ with a thermal resistance breakdown of the geometry. *UM1* and *UM2* represent the upper mount sections. *LEG1* indicates the mid-section. *LM1* and *LM2* represent the lower mount. Flexural elements are labelled *F1* to *F4*.

However, it is important to recognize from Eq. 3 that by lowering $R_{mounting}$ more of the total heat now flows through the part to the module frame ($Q_{mounting}$), which for the same geometry and coefficient of thermal expansion α can increase the mounting thermal expansion dL compared to its original length L *(Eq. 4)*. This may additionally allow more heat to reach the module frame, which can move and distort the part.

$$\frac{dL}{L} = \alpha \cdot dT = \alpha \cdot Q_{mounting} R_{mounting} \qquad \text{Eq. 4}$$

2.2. Thermal Shortcut Mounting Variation

In the thermal shortcut case, one lowers $R_{mounting}$ by decoupling the heat transfer path from the stiffness path. Since the flexural interfaces generally account for most of the error, these features can be shortcut (Figure 3). Alternatively, the full kinematic mount or even the entire module may be shortcut if length allows. Of course, the stiffness of the shortcut should be low compared to the stiffness of the flexure.

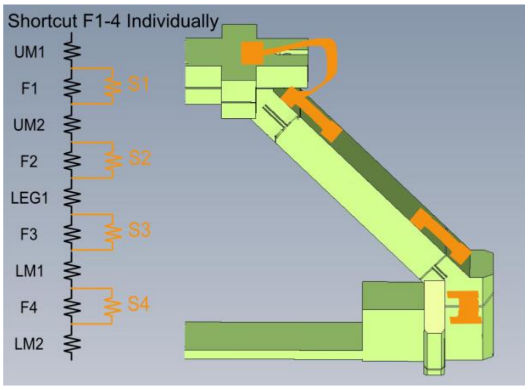

Figure 3. Kinematic mount half $R_{mounting}$ with thermal shortcuts *S1*, *S2*, *S3*, *S4* (orange) in parallel to flexural features *F1*, *F2*, *F3*, *F4*.

2.3. Isolator to Thermal Shortcut Mounting Variation

In order to maintain the original heat load to the frame but with effectively less thermal drift, one should add resistance *ISO1* between the heat source and the mount, followed by a shortcut, as indicated in Figure 4. Importantly, adding resistance between the mount and the module frame increases the average temperature and deformation of the mount and is not desired.

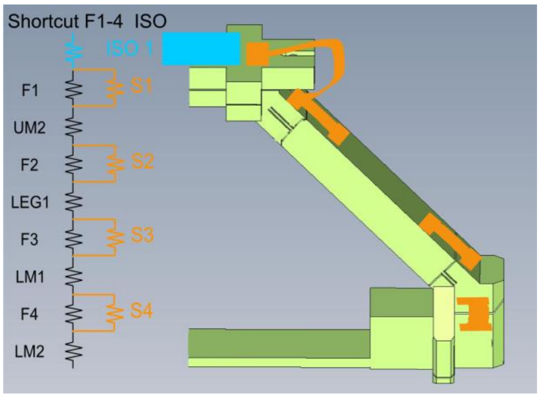

Figure 4. Kinematic mount half $R_{mounting}$ with schematic isolator *ISO1* (blue) on the component side of the mount and thermal shortcuts *S1*, *S2*, *S3*, *S4* (orange) in parallel to flexural features *F1*, *F2*, *F3*, *F4*. [1]

3. Convection, Gas Conduction and Radiation Modifications

Given local improvements to conductive routing in the mounts, exchange to the shield can be maximized by increasing local pressure to increase gas conduction or forcing additional local convection. Radiation exchange can be increased by using high emissivity coatings and by increasing the temperature difference with a lower inner shield temperature. At the same time, the reference frame should have low emissivity and minimal area exposure to the component.

4. Conclusion

By integrating all of the strategies presented above, one potential thermal architecture for minimizing thermal positioning errors of a highly sensitive part within a vacuum environment is concluded. A position critical part, having thermal shortcuts attached between the part and its mounts, transports heat directly to a cooler without heating the mounting elements or the module frame. Further, this part is thermally isolated from the module frame using high thermal resistance elements between the part and its flexural mount. Finally, the part is isolated from the reference frame and the module frame with a heat shield to prevent heat exchange between the part and the frame environment. Many variations of this architecture are also possible to minimize thermal errors within machine tools.

It should be further concluded that by using simple resistance models to consider how to properly route heat within a system, it is possible to quickly develop machine architectures for vacuum environments which limit thermal deformations and drift.

References

[1] Figueredo S, and Laufer T. Optical Device and Lithography System. Carl Zeiss SMT GmbH, assignee. Patent WO2015014947