Dynamic Thermal Center for High Precision Applications

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Abstract

Thermal effects are one of the main error sources in high precision systems. The time dependent thermal behavior of precision systems and the corresponding positioning uncertainty is an important aspect and often claims a large part of the available positioning budget. One way to deal with this issue is using real-time error-compensation methods that combine measured temperatures with knowledge of the thermo-elastic behavior of the corresponding system. The thermal induced time varying deformations are calculated real-time by the error compensation model based on measured temperatures. The real time signal can be used to compensate the thermal induced error if the application contains an active element. Also is shown that model reduction techniques can be used to derive optimal sensor positions and the thermal induced error compensation model. If the application is not able to use active compensation, directional compliant passive mounts at specific positions can result in a thermal center that not only holds for homogeneous temperate variation, but also for time varying temperature distributions. This paper shows how thermal behavior should be analyzed to derive a geometry with directional compliant mounts that is less sensitive to thermal transients.

1 Error compensation

The relation between the deformation of interest $\mathbf{p}(t)$ and the temperature distribution vector $\mathbf{T}(t)$ of the system is given by

Eq. 1 $$\mathbf{p}(t) = \mathbf{S}_{T\rightarrow P}\,\mathbf{T}(t)$$

The aim is to establish a model in order to find a sufficiently accurate estimate of the deformation $\mathbf{p}(t)$

Eq. 2 $$\mathbf{p}(t) \approx \hat{\mathbf{p}}(t) = \mathbf{C}_{\text{correction-model}}\,\mathbf{T}_{\text{sensors}}(t)$$

Where the measured temperatures are given by $\mathbf{T}_{\text{sensors}}(t)$. The number of sensors is minimized given a certain estimation accuracy (size $\mathbf{T}_{\text{sensors}}(t)$ is significantly smaller than size **T**(t)). The high number of m states of the numerical approximation can be rewritten into m states (**z**(t)) using projection matrix $\mathbf{\Phi}$

Eq. 3 $\mathbf{T}(t) = \mathbf{\Phi}\,\mathbf{z}(t).$

The columns of the projection matrix contain temperature distributions. The idea behind model reduction is using a selection of n projection shapes (temperature distributions), where n<<m, that describe the dominant dynamic thermal behavior. The temperature distribution can now be estimated with

Eq. 4 $\hat{\mathbf{T}}_m(t) = \mathbf{\Phi}_{m\times n}\,\mathbf{z}_n(t).$

The limited set of k temperature sensors can be described with

Eq. 5 $\mathbf{T}_{sensors}(t) = \mathbf{\Phi}_{k\times m}\,\mathbf{z}_m(t).$

Combining Eq. 4 and Eq. 5, an estimation in the least squares sense of the number of reduced states $\hat{\mathbf{z}}_n(t)$ can be made using the k temperature sensors

Eq. 6 $\hat{\mathbf{z}}_n(t) = \mathbf{\Phi}^{*-1}_{k\times n}\,\mathbf{T}_{sensors}(t)$ where $\mathbf{\Phi}^{*-1}_{k\times n}$ is the pseudo inverse

$\mathbf{\Phi}_{k\times n}$ is obtained from $\mathbf{\Phi}$ by selecting the n corresponding columns (linked to the selected states) and the corresponding rows (linked to the selected sensor positions). Deformation of interest is approximated substituting Eq. 6 and Eq. 4 in Eq. 2 resulting in

Eq. 7 $\hat{\mathbf{p}}(t) = \mathbf{S}_{T\rightarrow P}\cdot\mathbf{\Phi}_{m\times n}\cdot\mathbf{\Phi}^{*-1}_{k\times n}\cdot\mathbf{T}_{sensors}(t)$

Hence, the compensation model (see Eq. 2) we are aiming for is

Eq. 8 $\mathbf{C}_{correction-model} = \mathbf{S}_{T\rightarrow P}\cdot\mathbf{\Phi}_{m\times n}\cdot\mathbf{\Phi}^{*-1}_{k\times n}$

The sensitivity of the temperature sensors for the temperature distributions is position depend this is used to get an optimal configuration. In general the sensor configuration should be chosen such that temperature distributions of the relevant states can be distinguished best, this is achieved by positioning the sensors such that condition number of $\left(\mathbf{\Phi}^{T}_{k\times n}\mathbf{\Phi}_{k\times n}\right)$ is minimized. Error compensation is evaluated using a C-shaped setup, see figure 1 left. This setup measures the relevant in-plane frame deformations. A compensation model can therefore be validated. Further more, the frame is equipped with a local foil heater to apply an additional heat load next to the temperature sensors and a correction model based on 2 projection shapes is shown. ambient heat load. In figure 1 on the right the performance improvement using 2

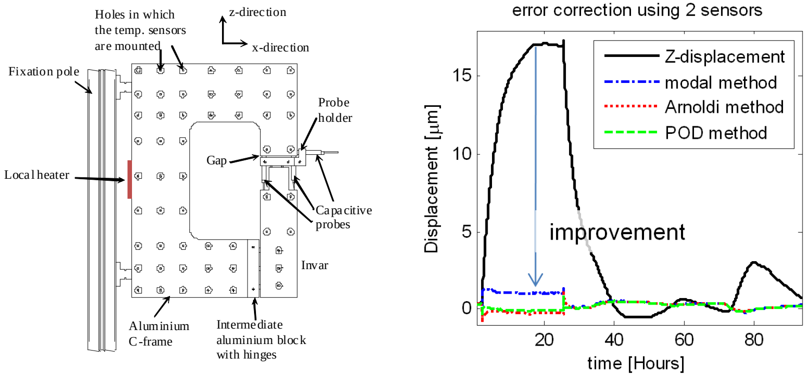

Figure 1 *left)* Mirror mechanism with a spider *right)* Measured z-displacement and the improvement using 2 temperature sensors and a correction based on 2 thermal-mode-shapes, 2 Arnoldi projection shapes and 2 POD-based projection shapes.

2 dynamic thermal center

If the application is not suitable for error correction techniques e.g. because no active elements are available and position stability of a specific point on the construction is required, directional compliant (passive) mounts at specific positions should be used.

A conventional thermal center is a design with compliant mounts that is such that if the structure heats up homogeneously the point of interest is stable. The main shortcoming of thermal centers is that it cannot deal with temperature gradients over a construction and therefore also not with thermal transients. A 'dynamic-thermal-center' is an extension to the conventional thermal-center that can deal with these thermo-dynamics. This can reduce the need for other measures like cooling and shielding or the use of special low expansion materials.

Assume we have a discrete representation (e.g. a FE-model) of a thermal system with *n* degrees of freedom (DOF). Than the complete thermal behavior is described with the vector $\mathbf{T}_{n\times1}(t)$, containing *n* temperature degrees of freedom. The thermal induced deformations of the structure can be calculated by post-multiplying the thermo-mechanical coupling matrix $\mathbf{S}_{T\rightarrow P}$ with the vector $\mathbf{T}_{n\times1}(t)$, see equation 1. A performance point (the thermal center) has often more DOF. In this paper we use p(t) to be one DOF for convenience of notation. Now conventional thermal centers have the following property, see equation 9. If the temperature transients occur according to equation 9, i.e. homogenous heating up or cooling down, a

Eq. 9 $$p(t) = \mathbf{S}_{T\rightarrow p} \cdot \mathbf{T}(t) \quad \Rightarrow \quad 0 = \mathbf{S}_{T\rightarrow p} \cdot \left(\alpha(t) \cdot \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix}_{n\times 1} \right)$$

thermal center will work properly for any *α(t)*. If gradients occur the temperatures cannot longer be described by α(t) times ones. The actual thermal dynamics $\mathbf{T}_{m\times 1}(t)$ can be approximated using a small set of size *n (n<<m)* of projection shapes using the POD method, a model reduction technique that derives its projection shapes from a time record of a typical thermal behavior. We record the thermal time behavior using simulation or measurement including pre-knowledge of heat-loads and how these will vary in time. A matrix $\mathbf{X}_{\mathbf{m\times r}}$ is constructed containing the *m* temperatures at *r* different time samples. The singular value decomposition of $\mathbf{X}_{\mathbf{m\times r}}$ gives the projection shapes in **U**

Eq. 10 $$\mathbf{X}_{m\times r} = \mathbf{U}_{m\times m} \mathbf{\Sigma}_{m\times r} \mathbf{V}_{r\times r}$$

The important thermo-dynamics is described with only the first n (n<<m) shapes, how many of these shapes are required can be seen in the singular values σ on the diagonal of Σ. n is picked such that $\sigma_n >> \sigma_{n+1}$. If the matrix $\mathbf{X}_{\mathbf{m\times r}}$ contains representative temperature behavior the actual thermo dynamics is approximately described with the fist *n* columns of **U**

Eq. 11 $$\mathbf{T}_{m\times 1}(t) \approx \mathbf{U}_{m\times n} \cdot [\alpha_1(t), \alpha_2(t), \ldots, \alpha_n(t)]^{\mathrm{T}}$$

If the structural properties of the system is designed such that equation 12 is met,

Eq. 12 $$[0 \quad \cdots \quad 0]_{1\times n} = \mathbf{S}_{T\rightarrow p\,(1\times m)} \cdot \mathbf{U}_{m\times n}$$

the structure has a performance point that is insensitive for the thermo-dynamics as described by temperature shapes (columns of **U**). The designer can calculate the deformations caused by the temperature shapes of the non-suspended structure to see how the suspension should be configured such that equation 12 is met, also numerical optimization can help in making this design. If a dynamic-thermal center can be obtained depends on the complexity of the thermo-dynamics and the design freedom. This paper has shown how temperature shapes dominating the thermal transient can be derived, and it is proposed that the designer used these deformations to design its suspension in contrary to designing the suspension such that the device is only insensitive for homogenous heating up improving performance.