MULTIPOINT TEMPERATURE CONTROL USING THERMOELECTRIC MODULES

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Abstract

Temperature control is a critical issue in precision engineering, especially for metrology structures and metrology frames. While oil shower and air showers have been shown to achieve millikelvin temperature stability, some applications do not permit oil shower or air shower systems (e.g. clean room environments). We demonstrate that by adding active temperature control to a structure, using thermoelectric devices for cooling or heating, we can maintain a structure at a more uniform temperature despite environmental temperature fluctuations. While it is not possible to maintain completely uniform temperature, it is possible to maintain temperature at selected points in the structure, where the sensors and actuators are located. Our objective is to demonstrate millikelvin temperature stability despite non-uniform external thermal disturbances. Some of the control issues that arise are cross coupling between different sensors and actuators, and effect of bias and drift of sensors (especially at millikelvin resolution). The analysis is based on a state variable finite difference thermal model. While state-space based control design may better handle cross coupling in the dynamics of the thermal system, simpler PID type controllers are easier to implement and test. The major advantages with active temperature control are that by separating the functions of temperature control from structural stability, one can choose materials for metrology structures based on structural criteria, independent of thermal properties. We will show initial experiments using a 4×4 array of thermoelectric coolers to control the temperature of an aluminum plate despite environmental disturbances. The results and control methods can be extended to large structures, such as metrology frames in lithography steppers. The advantages of this approach are not only better temperature control, but also superior dimensional control using inexpensive materials, and also more rapid thermal equilibration during equipment startup and shutdown.

Introduction

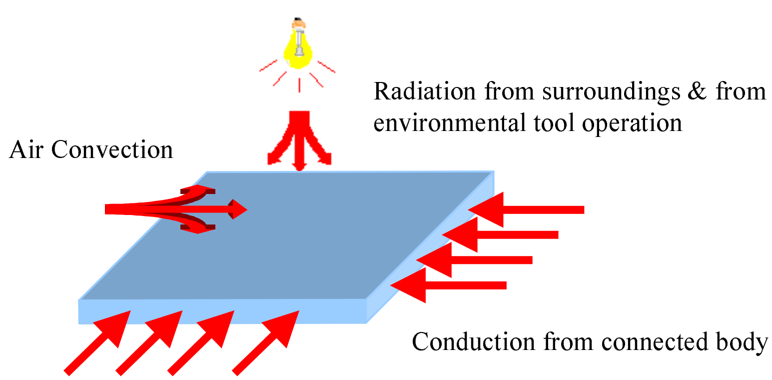

Fig. 1 Environmental Thermal Disturbances

Thermally induced errors in precision mechanical structures are a major part of the error budget in precision mechanical systems, especially with lithography applications. With the increasing demand for improved minimum critical dimension (CD) in semi-conductor fabrication, the desire to maintain a dimensional stability of 10% of the CD (currently 0.18 μm) becomes increasingly challenging. In spite of the manufacturers' effort, there are always some residual thermal displacements that are related to coefficient of thermal expansion (CTE) of the materials of the structure, which is subject to the fluctuations of the surroundings. Therefore, it is desirable to maintain structures at a uniform temperature,

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This work is supported by DOD/ARO DAAD-19-99-1-0196

regardless of environment. As an example, consider a 100mm square structure with a maximum 10nm of dimensional strain allowable to thermal effects. If the structure is made of super-invar (with a CTE of 0.63×10^{-6}/K), it is necessary to maintain its temperature at 160mK; however if the structure is made of aluminum (CTE of 22.5×10^{-6}/K), it is necessary to maintain the temperature should be kept within 5mK. However, aluminum has better specific stiffness, and is therefore more desirable mechanically. Active thermal control using a feedback control system emerges as a logical and practical solution.

Current techniques in the large equipment is to use air or oil shower to maintain the temperature; oil showers are not desirable in a clean room environment. Commercially available thermoelectric coolers (TEC) exploiting the Peltier effect and acting like solid-state heat pump with no moving parts are a very nearly ideal solution for small temperature ranges. With TECs, we can control structure temperature slightly above and below ambient temperature just by controlling current to the TEC; this allows isolation of a structure from possibly turbulent heat exchangers. We will describe the modeling of the system (4×4 TECs), and a proof-of-concept experiment and simulations for multipoint temperature control.

Heat transfer calculation

Consider the calculation shown in Figure 2.

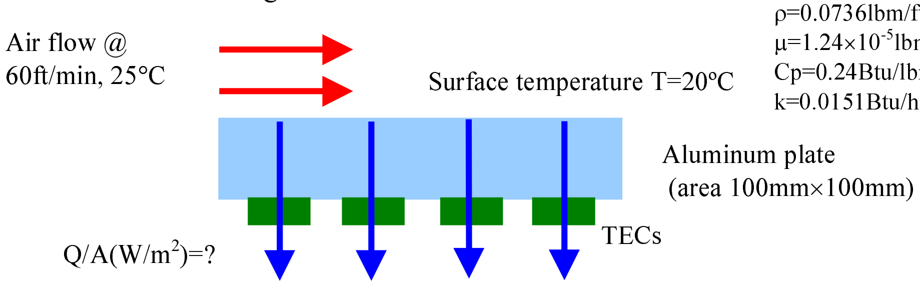


Fig. 2 Heat Transfer Calculation Setup

The heat convection coefficient of the surrounding air $$h=\frac{N_u\times k}{L} \tag{1}$$

For the design purpose, take average value for Nusselt number $$N_{uL}=0.664\times \mathrm{Re}^{1/2}\times \mathrm{Pr}^{1/3} \tag{2}$$

Equation (2) is applied when Reynolds number $\mathrm{Re}<2\times10^5$, where $$\mathrm{Re}=Lv\rho/\mu=1947 \tag{3}$$

We can also calculate Prandtl number Pr as $$\mathrm{Pr}=\mu C_p/k=0.70951 \tag{4}$$

From (2), (3) and (4), we can obtain $N_{uL}=26.132$ and $h=1.203\,$Btu/hr.°F.ft^2 $=7.22\,$W/m^{2}K. With a total area of 0.01m^2, we have $Q=h\times A\times\Delta T=0.361\,$W. The air velocity of 60 ft/min is typical in laminar flow clean rooms (between 60 and 100 ft/min at the face of the HEPA filters). The average cooling power of a Ferrotec-USA module TE6302/065/018A is 5W, so an array of these modules provides more than sufficient cooling or heating power.

Experimental setup

Figure 3 shows a schematic concept for a temperature control experiment.

The temperature range we need to control is not large (±5 K), however the requirement for temperature precision is at millikelvin level. We choose thermistors for their high sensitivity and long term stability.

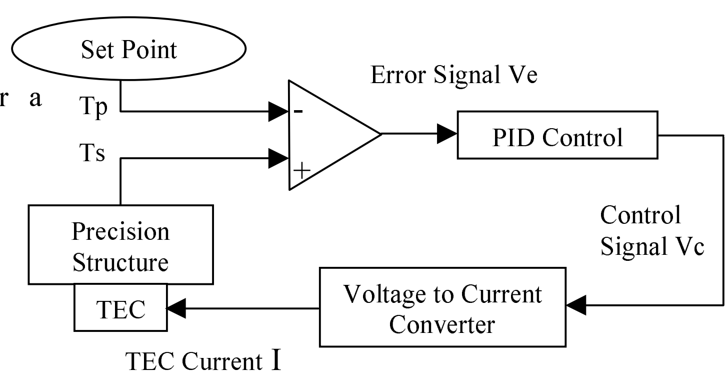
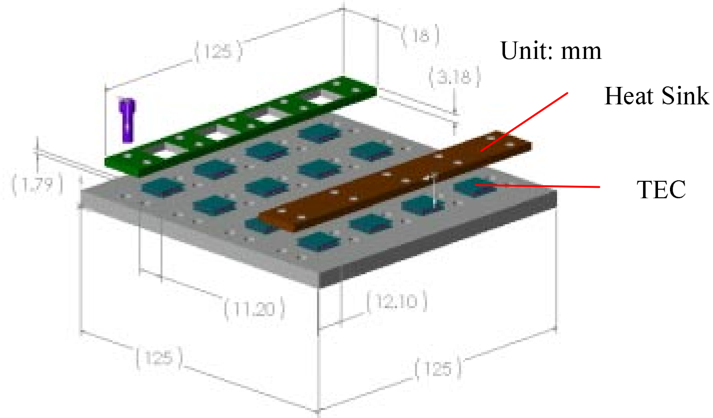


Fig. 3 Experimental block diagram



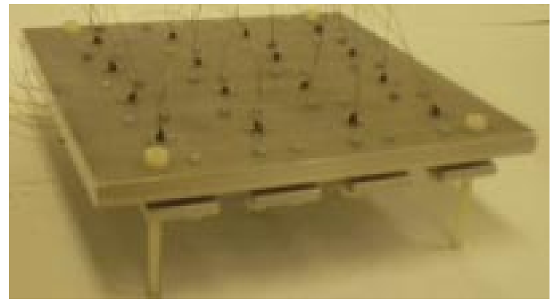


Fig. 4 Test Structure Assembly View

Fig. 5 Photograph of Test Structure

The test structure is an aluminum plate, shown in Figure 4 and Figure 5.

Finite Difference Model

The test structure is virtually cut into 4×4 parts as figure 6 shows and the sixteen elements are controlled by individual TECs and the temperature is measured individually by thermistors. However there exists thermal coupling between these elements. Coupling between diagonal elements (e.g. [1,1] and [2,2]) is smaller than between adjacent elements, and is omitted in the model. The effects of bolting holes are also omitted in the model. Since the system involves both conduction and surface convection effects, it is necessary to determine the Biot number that provides a measure of the temperature drop in the solid relative to the temperature difference between the surface and the fluid.

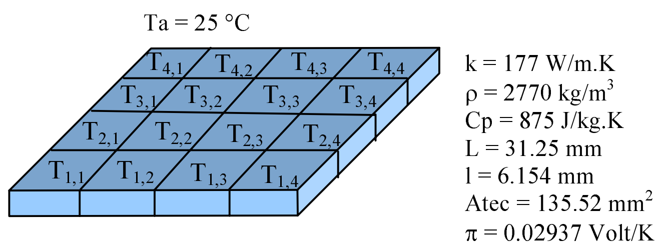


Fig. 6 Finite Difference Model

$$Bi = hL / k = 0.00334 < 0.1 \tag{5}$$

Hence the assumption of a uniform temperature distribution for each element is reasonable.
There are three types of elements for this model: inner ([2,2], [2,3], [3,2], [3,3]); corner ([1,1], [1,4], [4,1], [4,4]); side ([1,2], [1,3], [2,1], [3,1], [4,2], [4,3], [2,4], [3,4]).

- **Inner Nodes**

Take [2,2] as an example. By conservation of energy, we can obtain the following equation

$$\dot{T}_{2,2} = \frac{k}{\rho L^2 C_p}(T_{1,2} + T_{2,1} + T_{2,3} + T_{3,2} - 4T_{2,2}) - \frac{h}{\rho L^2 l C_p}(2L^2 - A_{tec})(T_{2,2} - T_a) - \frac{\pi}{\rho L^2 l C_p} I_{2,2} \tag{6}$$

- **Corner Nodes**

Take [2,2] as an example. By conservation of energy, we can obtain the following equation

$$\dot{T}_{1,1} = \frac{k}{\rho L^2 C_p}(T_{2,1} + T_{1,2} - 2T_{1,1}) - \frac{h}{\rho L^2 l C_p}(2L^2 - A_{tec} + 2Ll)(T_{1,1} - T_a) - \frac{\pi}{\rho L^2 l C_p} I_{1,1} \tag{7}$$

- **Side Nodes**

Take [1,2] as an example. By conservation of energy, we can obtain the following equation

$$\dot{T}_{1,2} = \frac{k}{\rho L^2 C_p}(T_{1,1} + T_{1,3} + T_{2,2} - 3T_{1,2}) - \frac{h}{\rho L^2 l C_p}(2L^2 - A_{tec} + Ll)(T_{1,2} - T_a) - \frac{\pi}{\rho L^2 l C_p} I_{1,2} \tag{8}$$

In equation (6), (7) and (8), the k-term is related with the heat conduction between different elements, h-term heat convection from the surroundings, π-term heat drawn by TEC. Here we omit the resistance and conductance effects of TEC to simplify the problem and assume that heat sinks attached to TECs work perfectly. It is also assumed that the temperature-related coefficients k, h, Cp and π are constant since the temperature range is within ±5 K.

Plugging in the value of parameters, we obtain the state-space equations of the system as follows.

$$\dot{\mathrm{T}} = \mathrm{AT} + \mathrm{BI} + \mathrm{D}T_a \tag{9}$$

$$\dot{\mathrm{T}} = \left(\dot{T}_{1,1} \quad \dot{T}_{1,2} \quad \dot{T}_{1,3} \quad \dot{T}_{1,4} \quad \dot{T}_{2,1} \quad \dot{T}_{2,2} \quad \dot{T}_{2,3} \quad \dot{T}_{2,4} \quad \dot{T}_{3,1} \quad \dot{T}_{3,2} \quad \dot{T}_{3,3} \quad \dot{T}_{3,4} \quad \dot{T}_{4,1} \quad \dot{T}_{4,2} \quad \dot{T}_{4,3} \quad \dot{T}_{4,4}\right)^T$$

$$\mathrm{T} = \left(T_{1,1} \quad T_{1,2} \quad T_{1,3} \quad T_{1,4} \quad T_{2,1} \quad T_{2,2} \quad T_{2,3} \quad T_{2,4} \quad T_{3,1} \quad T_{3,2} \quad T_{3,3} \quad T_{3,4} \quad T_{4,1} \quad T_{4,2} \quad T_{4,3} \quad T_{4,4}\right)^T$$

$$\mathrm{I} = \left(I_{1,1} \quad I_{1,2} \quad I_{1,3} \quad I_{1,4} \quad I_{2,1} \quad I_{2,2} \quad I_{2,3} \quad I_{2,4} \quad I_{3,1} \quad I_{3,2} \quad I_{3,3} \quad I_{3,4} \quad I_{4,1} \quad I_{4,2} \quad I_{4,3} \quad I_{4,4}\right)^T$$

$$A = \begin{pmatrix} \Phi & 0.0748E_4 & 0 & 0 \\ 0.0748E_4 & \Gamma & 0.0748E_4 & 0 \\ 0 & 0.0748E_4 & \Gamma & 0.0748E_4 \\ 0 & 0 & 0.0748E_4 & \Phi \end{pmatrix} \qquad \mathrm{B} = -0.00202\mathrm{E}_{16}\,\mathrm{I} \qquad \mathrm{D} = \left(\mathrm{D}_1 \quad \mathrm{D}_2 \quad \mathrm{D}_2 \quad \mathrm{D}_1\right)^T$$

$$\Phi = \begin{pmatrix} -0.1506914 & 0.0748 & 0 & 0 \\ 0.0748 & -0.2253961 & 0.0748 & 0 \\ 0 & 0.0748 & -0.2253961 & 0.0748 \\ 0 & 0 & 0.0748 & -0.1506914 \end{pmatrix} \qquad \mathrm{D}_1 = \begin{pmatrix} 0.0010914 \\ 0.0009961 \\ 0.0009961 \\ 0.0010914 \end{pmatrix}$$

$$\Gamma = \begin{pmatrix} -0.2253961 & 0.0748 & 0 & 0 \\ 0.0748 & -0.3001008 & 0.0748 & 0 \\ 0 & 0.0748 & -0.3001008 & 0.0748 \\ 0 & 0 & 0.0748 & -0.2253961 \end{pmatrix} \qquad \mathrm{D}_2 = \begin{pmatrix} 0.0009961 \\ 0.0009008 \\ 0.0009008 \\ 0.0009961 \end{pmatrix}$$

Where E_4 is a 4×4 identity matrix, 0 is a 4×4 zero matrix, E_{16} is a 16×16 identity matrix, T_a is the temperature of the surrounding air. This system is linear and controllable.

Summary

The results of the simulations and experiments will be presented at the conference.

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