

Verification of Thermal System Performance for Control Applications Using TMG Finite Element Simulation and MATLAB

Michael Saeger
ATA Engineering, Inc.

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ABSTRACT

Many real world engineering systems are sensitive to temperature, and temperature control is vital to the success and operation of a broad spectrum of engineering applications. This paper investigates the use of numerically generated frequency response data to simulate the control system behavior of a simple but realistic finite element based nonlinear thermal model.

Using an IDEAS TMG finite element model, a thermal control system Bode plot was computed. The Bode plot was then used to determine the transfer function of the thermal system and design an appropriate control compensator to implement thermal control.

The performance of the compensated thermal system was then predicted first by MATLAB, and second by TMG. The response predicted by MATLAB using transfer functions was corroborated by its close agreement with a TMG finite element transient response simulation.

Nonlinear thermal effects, such as heat transfer by radiation, are addressed, and their impact on control system performance is explored. Lastly, the advantages of using a transfer function approach to control system analysis, as opposed to control tuning by trial and error, are outlined, and possibilities are suggested for extending the methods and techniques presented in this work to other types of thermal control systems.

INTRODUCTION

Methods and practices for designing control compensators for linear, time-independent systems are well established by control theory [1][2][3]. However, application of control theory to a system requires knowledge about how that system responds when acted on by a controller. This knowledge is described mathematically by the transfer function of the system (Laplace domain ratio of system response to system input). This paper presents a control system analysis and simulation of a simple optical bench model through

TMG finite element analysis and MATLAB. The temperature control of this optical bench is accomplished using a PID controller. A feedback control block diagram for this system is given in Figure 1.

In order to apply the principles of control theory to this system, the transfer function of the plant (in this case the optical bench) must be determined. This was done by using a TMG finite element model in conjunction with a custom user-written subroutine to generate a Bode plot for the optical bench [4]. Transfer function extraction was done using MATLAB. Finally, a PID controller and closed loop feedback control was added to the system. The control system response to a step change in set point temperature was computed by TMG (based on the finite element model) and compared to the step response predicted by MATLAB (based on the Bode plot-derived transfer function).

The focus of this paper is to investigate the accuracy of a linearized, numerically generated, finite element based transfer function. A sample PID controller is included in the model predictions, but the tuning of that controller is another subject and will not be discussed here. A thorough treatment of methods and practices for control system tuning and optimization is provided by Ogata [1], Nise [2], and Chau [3].

MODEL LINEARIZATION

Although transfer functions only apply to linear, time independent systems, many real world systems are nonlinear. One approach to dealing with nonlinear systems is to linearize them by determining a set of baseline conditions in the vicinity of a particular operating point. If system perturbations are small then the state of the system will remain close to the operating point and the system will react in a nearly linear fashion. This is the approach that will be taken in the control system analysis of the nonlinear optical bench model; however, alternate approaches to linearizing a thermal model are given by Saeger [4].

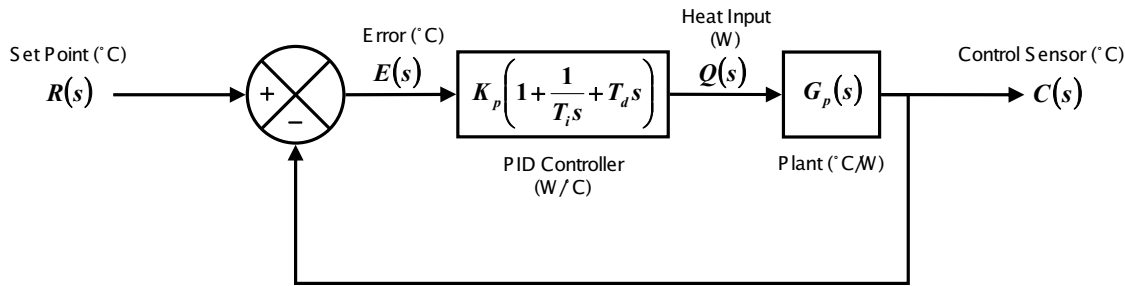


FIGURE 1. Control system block diagram for the optical bench system. The optical bench is the plant and the control compensator is a PID controller.

CONTROL SYSTEM SIMULATION OF A SIMPLE OPTICAL BENCH

A diagram of the optical bench system under investigation is shown in Figure 2. The optical bench model consists of a simple optical bench mounted inside a box-shaped enclosure. One side of the enclosure box is maintained at 0°C. The optical bench has a control heater on one side and a control sensor near the other end. The bench is mounted inside the enclosure using three standoffs. The size of the enclosure box is 14.5 cm wide, 9.5 cm high, and 11 cm deep, and it is made out of 2 mm thick aluminum. The optical bench is made out of Kovar, and the standoffs are made out of 4 mm diameter titanium 6Al4V rod. Heat exchange by radiation inside the box is included in the analysis. The emissivity values are 0.25 for the box interior, 0.9 for the heater surface and optical bench surface seen directly by the heater, and 0.5 for the rest of the optical bench.

It is assumed that the goal of the thermal control system is to maintain the temperature at the sensor location at 80°C. The control compensator that is used to achieve this goal is a PID controller. A control system block

diagram for this system is pictured in Figure 1.

Control system analysis requires determination of the plant transfer function $G_p(s)$. This can be done by generating a Bode plot of the thermal system based on the control heater as the input and the temperature sensor as the output.

The task of obtaining a Bode plot for an arbitrary thermal system is not trivial. Saeger [4] presents a method for calculating Bode plot data from a thermal finite element model using I-DEAS TMG and a custom user-written subroutine. This method was applied to the optical bench system shown in Figure 2.

A curve fit was performed on the numerically generated Bode plot data to obtain a functional representation of the plant transfer function. Based on this transfer function, control system analysis was done using the Control System Toolbox functions of MATLAB. Using MATLAB tools, three PID compensators were created: one stable, one marginally stable, and one unstable. For each of these compensators, the system response to a step change in set point was predicted, first using

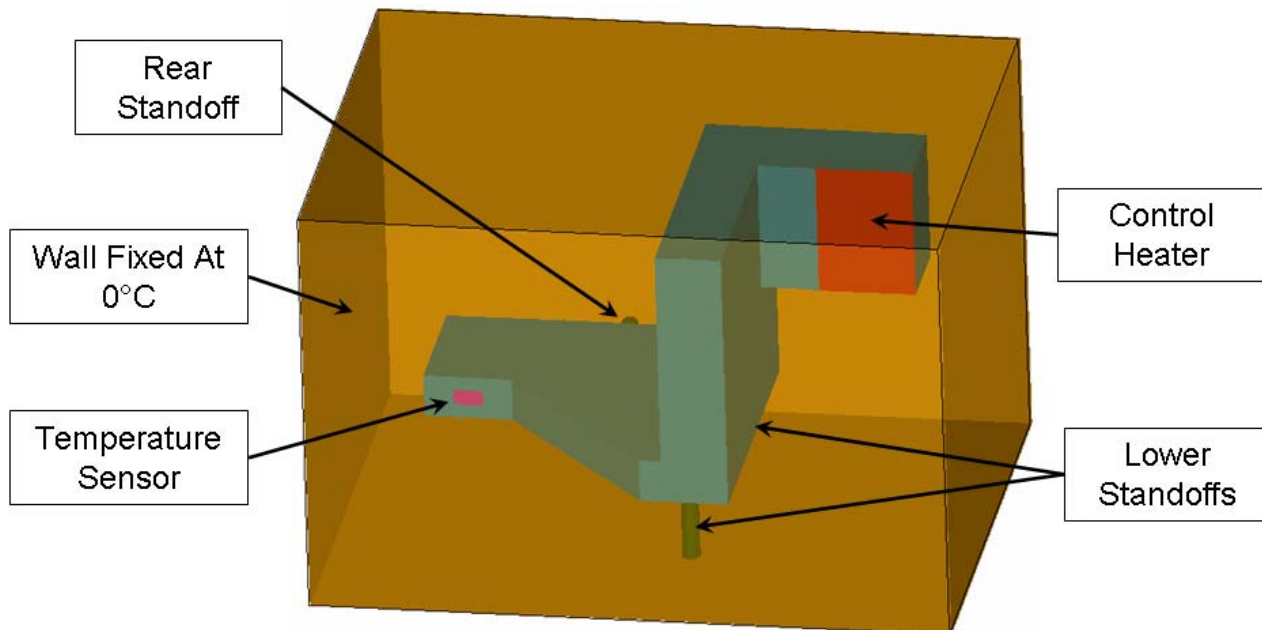


FIGURE 2. Diagram of the optical bench model including heater, sensor, and fixed temperature wall.

MATLAB (based the plant and compensator transfer functions) and second using TMG (based on the finite element model). Agreement between MATLAB and TMG response predictions validates the computed plant transfer function and the ability of MATLAB to perform compensator tuning on a finite element based thermal model. Figure 3 provides a schematic representation of the procedure that was followed.

As discussed by Saeger [4], multiple Bode plots based on different meshes and/or solution parameters are needed to assess the frequency range over which confidence in the numerical Bode plot results is justified.

Two meshes were created for the optical bench. One

mesh consisted of brick and wedge elements, and the other was made up of tetrahedron elements. The two optical bench meshes are shown in Figure 4.

Because this thermal system involves nonlinear heat transfer by radiation, the first step in obtaining a Bode plot is establishing a baseline condition. The baseline heater power needed to maintain the temperature of the sensor element at the set point of 80°C was determined through iterative trial and error. The required baseline heater power was found to be 6.887 W. Imposing this heater power resulted in a calculated steady state temperature distribution of the optical bench model under baseline (typical operating) conditions. The

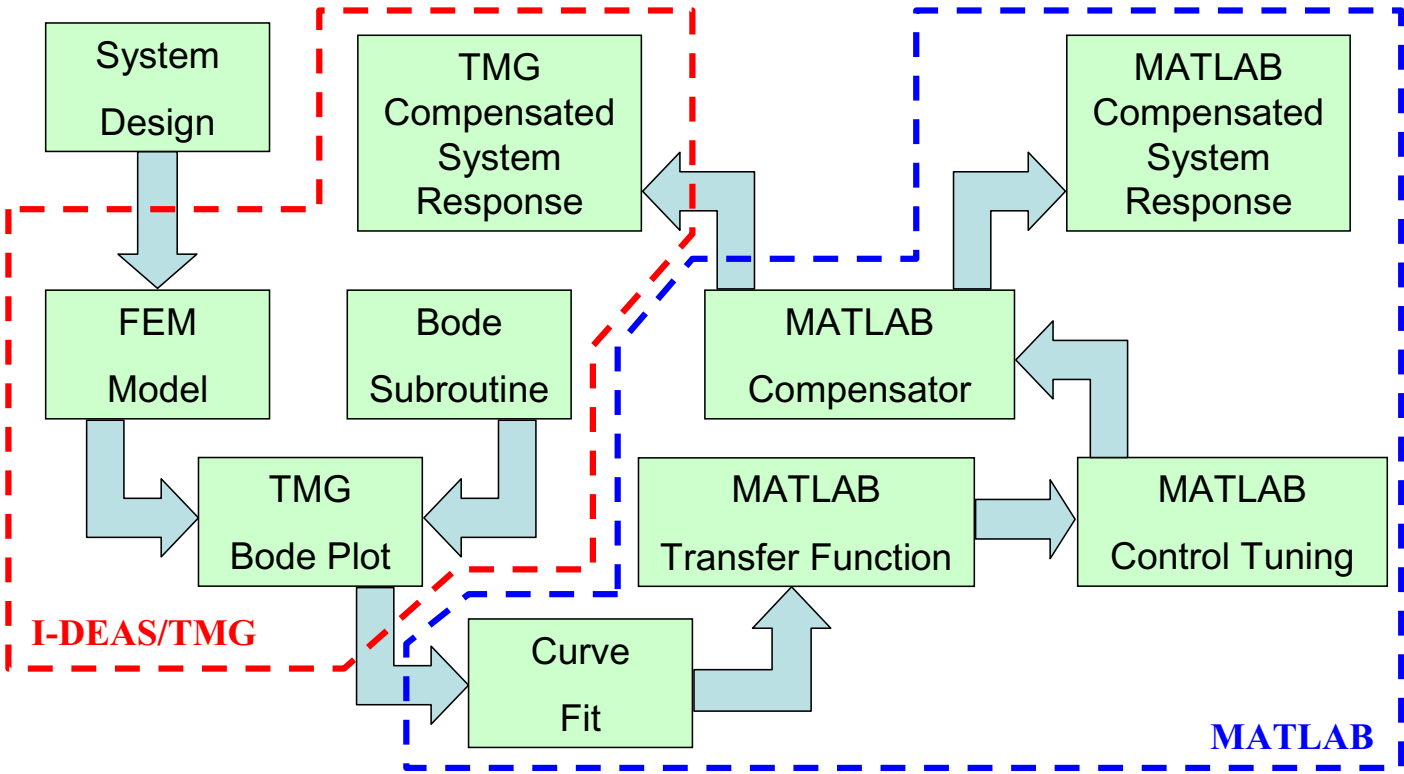


FIGURE 3. Flow chart of the optical bench control system analysis procedure.

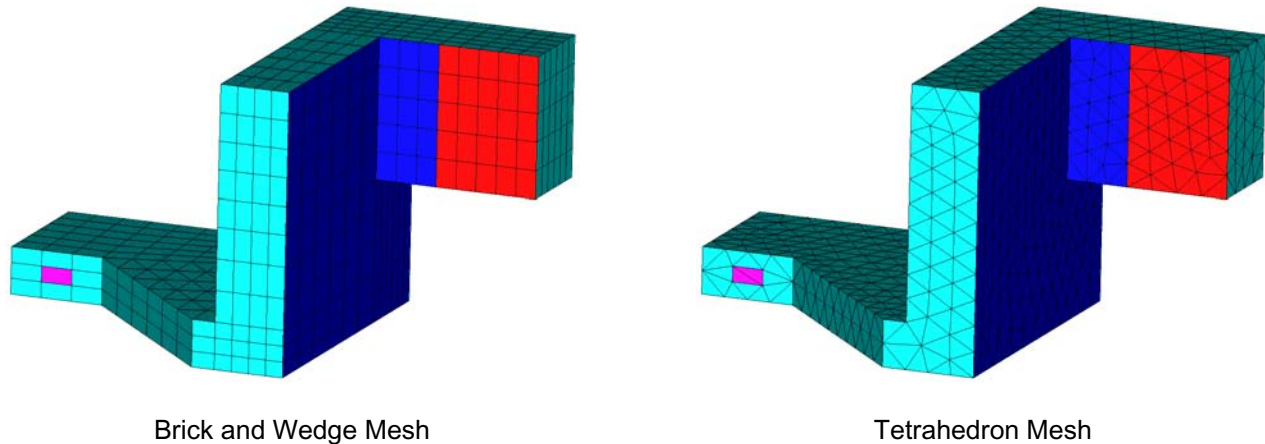


FIGURE 4. Finite element models of the optical bench.

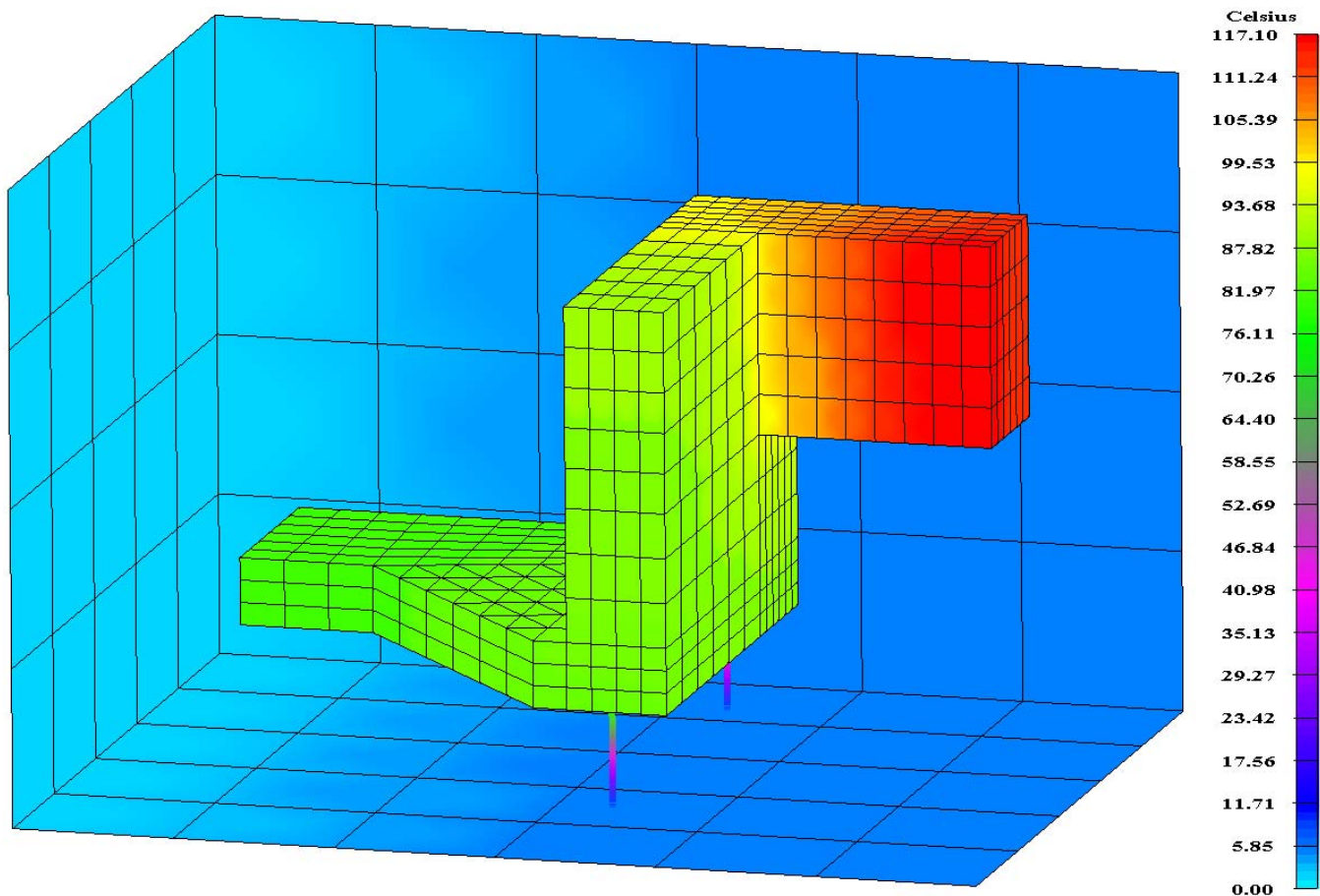


FIGURE 5. Baseline temperature distribution for the optical bench model based on 80°C set point at the sensor location (front side of the enclosure removed for clarity).

baseline temperature distribution is pictured in Figure 5.

Bode plots were constructed by applying sinusoidal heat load to the heater elements and measuring the response amplitude and phase at the sensor element. Because the optical bench model involves nonlinear heat transfer, the sinusoidal heat load was added to the constant-value baseline heat load, and the magnitude of the sinusoidal heat load was carefully chosen to ensure that the temperature fluctuations throughout the entire model (not just at the sensor location) would be small enough to keep the resulting response very nearly linear.

Four Bode plots were created for the optical bench model. For each of the two meshes, the TMG's Element Center conduction method was used to generate one Bode plot, and the Element CG method (with lumped capacitance) was used to generate another. In all cases, Backward-Forward transient integration was used. The four resulting Bode plots are presented in Figure 6.

It would be possible to create more Bode plots for this system using different meshes and solution parameters, but the excellent agreement between these four plots

provides confidence that the results are quite valid across the entire frequency range and that no further plots are needed

It should be noted that the characteristics of the Bode plots in Figure 6 are somewhat unusual, but not unexpected. The phase angle of the response initially drops in a typical fashion, but then partially recovers again. This is because conduction is the dominant mode of heat transfer at low frequencies but radiation becomes the dominant mode at high frequencies. Radiation is also responsible for the response magnitude leveling off at high frequencies instead of continuing to decrease as is often the case. The high frequency behavior indicated by the Bode plots in Figure 6 is a result of the fact that both the heater elements and the sensor elements are made of zero thickness (and hence zero heat capacity) shell elements with a direct conductance path between them (by radiation). If either the heater elements or the sensor element had finite heat capacity, or if there were no capacitance-free heat path between them (if the box enclosure emitted and absorbed as a blackbody, for example), then the response magnitude would continue to decrease at high frequencies.