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Control of temperature uniformity in the temperature chamber with centrifugal acceleration

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ABSTRACT

A novel method for control of temperature uniformity in the combined environmental testing is proposed. The structure of the temperature test chamber is introduced and the multi-input multi-output (MIMO) temperature control system is designed, in which the plant is approximated by the first-order plus time delay (FOPTD) model. The control objectives are summarized as making the average output temperature track the reference input and making the temperature at different spots track the average temperature. The controller is composed of two sub-controllers, each of which ensures the tracking performance of the average temperature and improves the uniformity of the temperature field, respectively. Both the simulation and experimental results show that the nonuniformity of the temperature field can be decreased effectively by the proposed method even if the temperature field is disturbed by centrifugal acceleration. The method provides an easy way to control the uniformity of the temperature field without decoupling and precise system identification.

1. Introduction

Components on the spacecraft are suffered from combined environment including linear acceleration, temperature, etc. It is very significant to do the combined environmental testing on the earth to improve the reliability of the spacecraft. Generally, device for the combined environmental testing, which involves linear acceleration and temperature field, is composed of a centrifuge and an environmental test chamber [1,2], in which multiple environmental factors are combined. The linear acceleration is simulated through centrifugal acceleration generated by the centrifuge and the test chamber is mounted at the end of the centrifuge arm. In this case, centrifugal acceleration will make the temperature field suffered from the combined effects of thermal buoyancy, rotational buoyancy and Coriolis force when the centrifuge is running [3], which makes the temperature distribution nonuniform in the test chamber. However, it is very important to keep the uniformity of the temperature field in the combined environmental testing.

Our previous study has revealed that the temperature nonuniformity can be decreased by stirring the air with a fan in the test chamber [4], but how to decrease it in a perspective of control approach has not been studied. Moreover, seldom has existing literature discussed the control of temperature uniformity in the combined environmental testing. Now a test chamber with multiple distributed heaters and temperature sensors is proposed and a multi-input multi-output (MIMO) temperature control system is built, whose plant have strong coupling effects. The aim of this study is to decrease the temperature nonuniformity in the test chamber with a MIMO control approach.

Generally, study on MIMO temperature control system focuses on decoupling or quasi-decoupling [5–10], and building an equivalent model of multiple single-input single-output (SISO) systems without coupling effects. Based on the idea of decoupling, Matsunaga et al. [11] studied the uniform temperature control for heating an aluminum plate. However, the decoupling must be guaranteed under the condition that precise plant model is obtained, which in turn makes the decoupler very complicated. An easy traditional method for uniformity control of temperature is dividing the heating space into several sections, each of which constructs an independent SISO subsystem [12]. Consequently, multiple SISO

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subsystems are built and the PID algorithm is applied without considering the coupling effects among the subsystems. This method belongs to the decentralized control [13,14], in which a diagonal controller is employed and multiple PID or other controllers are used. The problem for this is that the PID tuning of the multiple channels turns out to be hard [15–17]. In this case, Hirama et al. presented an evaluation function for decision of the best PID tuning sequence [18]. However, the PID tuning will still be very cumbersome if there are too many channels [19]. Based on the decentralized control, fuzzy control strategy of multiple channels for temperature control system in the furnace has also been employed in many studies [20–22]. However, the generation of the fuzzy rules will be very difficult if there are too many channels.

In this paper, a novel method for control of temperature uniformity is put forward considering the contributions of the inputs to the outputs. The advantage of this method is that the complicated process of decoupling and the precise identification of the system are not needed.

2. Plant of the temperature test chamber

2.1. Structure of the temperature test chamber

The structure of the temperature test chamber is shown in Fig. 1, which mainly consists of thermoelectric coolers (TECs), heat sinks, temperature sensors, etc. The enclosure in the center is the space which we care about.

TECs are adopted to be the actuators for heating and cooling because they meet the requirement of limited mounting space on the test chamber. TECs are solid-state energy converters based on the Seebeck phenomena, which can be used for cooling and heating without mechanical driving parts, compared to the conventional cooling methods [23]. When powered up, they absorb heat from the environment at their acting sides and dissipate heat to the environment at the other sides. The heating and cooling modes can be exchanged by changing the current polarity. The energy absorbed and dissipated at the two sides are relevant to the current passing through the TECs. However, the current direction in the TEC cannot be changed frequently because the dynamic thermal stress caused by this may damage the TEC. As a result, the decoupling of the system is not recommended because the decoupling control may lead to frequently alternating input current to the actuators.

Layout of the TECs and temperature sensors is shown in Fig. 1. The enclosure in the center, where all of the environmental factors couple, is the space which we care about. The aim of control is to decrease the temperature nonuniformity of the air in the enclosure. Eight TECs (named as TEC1, TEC2, . . ., TEC8) are distributed along the outside circumference of the test chamber, each of which can be controlled independently. Eight temperature sensors (named as S1, S2, . . ., S8) are assembled in the test chamber, which are arranged into two horizontal layers symmetrically. Relative position of the TECs and temperature sensors can be drawn as shown in Fig. 2, where the S1, S3, S5 and S7 lie in the lower layer, while the other sensors lie in the upper layer.

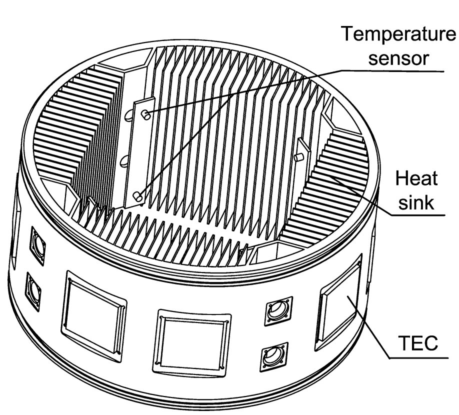

Fig. 1. Structure of the temperature test chamber.

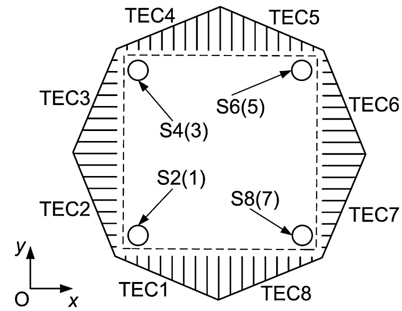

Fig. 2. Relative position of the TECs and temperature sensors.

2.2. Modeling of the temperature test chamber

The temperature control system is a multivariable system with eight inputs and eight outputs. The relationship between the inputs and outputs can be expressed as

$$\boldsymbol{Y}(s) = \boldsymbol{G}(s)\boldsymbol{U}(s), \tag{1}$$

where

$$\boldsymbol{G} = \begin{bmatrix} G_{11} & G_{12} & \cdots & G_{1n} \\ G_{21} & G_{22} & \cdots & G_{2n} \\ \vdots & \cdots & \ddots & \vdots \\ G_{n1} & G_{n2} & \cdots & G_{nn} \end{bmatrix} \tag{2}$$

is the plant. $\boldsymbol{U}(s)$ and $\boldsymbol{Y}(s)$ are the vectors of the inputs and outputs, respectively.

Generally, the plant of temperature control system can be approximated by the first-order plus time delay (FOPTD) model [24]

$$G_{ij} = \frac{k_{ij}e^{-\tau_{ij}s}}{T_{ij}s+1}, \quad (i, \quad j = 1,\ 2,\ \ldots,\ n), \tag{3}$$

where k_{ij} is the static gain, T_{ij} is the inertial time constant, and τ_{ij} is the pure time delay.

If only the mth $(m = 1,\ 2,\ \ldots,\ n)$ input is given as a step function $u_m(t) = 1 \quad (t > 0)$, then the ith output is obtained as

$$Y_i(s) = \sum_{j=1}^{n} G_{ij}(s)U_j(s) = \frac{k_{im}}{(T_{im}s+1)}e^{-\tau_{im}s} \cdot U_m(s) = \frac{k_{im}}{s(T_{im}s+1)}e^{-\tau_{im}s}. \tag{4}$$

Then the system turns into a single-input multi-output (SIMO) system. By applying the inverse Laplace transform to Eq. (4), the response in the time domain is obtained as

$$y_i(t) = k_{im}(1 - e^{-(t-\tau_{im})/T_{im}}). \tag{5}$$

By employing the nonlinear least-square fitting to the experimental output sequence y_i via Matlab with the model given in Eq. (5), the static gain k_{im}, inertial time constant T_{im} and pure time delay τ_{im} can be obtained. Similarly, the complete model $\boldsymbol{G}(s)$ can be obtained by carrying out experiments on the rest of the inputs in the same way.