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Designing the Controller Based On the Approach of Hedge Algebras and Application for Temperaturecontrol Problem of Slab

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ABSTRACT : *In this paper we present a method of designing the controller based on the approach of Hedge Algebras (HA) that mentioning the optimization of the controller parameters by Genetic Algorithm (GA). To illustrate the effectiveness of the design method we apply the problem of slab temperature control with assuming the mathematical model of the slab is as the transfer function model. The results of the research have been verified through simulation and have shown the possibility of being able to apply in practice.*

KEYWORDS -*Hedge Algebras, Genetic Algorithm,Controller,Slab, Transfer Function*

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I. INTRODUCTION

When designing logicallinguistic controller, it is the most important to ensure a semantic order relationship between linguistic elements. HA (Hedge Algebra) [1], [3] is an algebraic structure based on a linguistic rule whose semantics assure order relations. Based on HA, there are many applications that have been developed such as fuzzy database, classification, control, …[1], [3]. Because HA allows building a model calculation for LRBS-based controllers, it can beapplied in the field of control and automation [3]. According to the HA, linguistic terms are computed based on their semantic value which is always order and suitable for constructing computational models in approximation problems. The HA controllers will have the advantages of the fuzzy control, while promoting the advantages of computation based on the semantic validity of the language and the problem of intuitive thinking.

In this study, we present a method of designing the controller based on the approach of Hedge Algebras (HA) that mentioning the optimization of the controller parameters by Genetic Algorithm (GA). To illustrate the effectiveness of the design method we apply the problem of slab temperature control with assuming the mathematical model of the slab is as the transfer function model.

II. METHOD OF DESIGNING THE CONTROLLER BASED ON APPROACH OF HEDGE ALGEBRAS

Suppose we have a set of linguistic values of a certain linguistic variable which includes $\ldots < Very\ Negative < Negative < Litle\ Negative < \cdots < Zero < \cdots < Litle\ Positive < Positive < Very\ Positive < \cdots$These linguistic values appears in linguistic rule bases of approximation problems based on knowledge. Thus, it is necessary to have a strict computational structure which preserves the inherent order of the linguistic values. From this we can calculate the semantic relationship of the linguistic values in the rules.
HA [1], [3] is an orderly mathematical structure of the set of linguistic terms, the order relations are defined by the semantics of the linguistic terms in this aggregation. Quantifying the semantic validity of linguistic terms through semantic quantitative mapping functions - SQMs [5] allows a full description of the model of the rule set and the approximation reasoning process in a close and reasonable way [1],[3], [4].
Consider a fuzzy model given as LRBS:

$$\text{If } \mathcal{X}_1 = \mathrm{A}_{11} \text{ and } \ldots \text{ and } \mathcal{X}_\mathrm{m} = \mathrm{A}_{\mathrm{m}1} \text{ then } \mathcal{Y} = \mathrm{B}_1$$

$$\text{If } \mathcal{X}_1 = \mathrm{A}_{12} \text{ and } \ldots \text{ and } \mathcal{X}_\mathrm{m} = \mathrm{A}_{\mathrm{m}2} \text{ then } \mathcal{Y} = \mathrm{B}_2 \quad \text{(Eq. 1)}$$

…

$$\text{If } \mathcal{X}_1 = \mathrm{A}_{1\mathrm{n}} \text{ and } \ldots \text{ and } \mathcal{X}_\mathrm{m} = \mathrm{A}_{\mathrm{mn}} \text{ then } \mathcal{Y} = \mathrm{B}_\mathrm{p}$$

As $\mathcal{X}_1, \mathcal{X}_2, \ldots \mathcal{X}_\mathrm{m}$, and $\mathcal{Y}$ are linguistic variables, each linguistic variable $\mathcal{X}_\mathrm{i}$ belongs to the base space U_i and the linguistic variable $\mathcal{Y}$ is in the base space V; $\mathrm{A}_{\mathrm{ij}}, \mathrm{B}_\mathrm{k}$ $(\mathrm{i} = 1..\mathrm{m}, \mathrm{j} = 1..\mathrm{n}, \mathrm{k} = 1..\mathrm{p})$ are the linguistic values that belong to the corresponding base space. Each rule "If ... then", identifies a "fuzzy point" in the $\mathrm{Dom}(\mathcal{X}_1) \times \mathrm{Dom}(\mathcal{X}_2) \times \ldots \times \mathrm{Dom}(\mathcal{X}_\mathrm{m}) \times \mathrm{Dom}(\mathcal{Y})$. Then (Eq. 1) can be considered as a "hyper-surface" of $\mathrm{S}^{\mathrm{m}+1}_{\mathrm{fuzz}}$ in this space. According to the approaching of the HA theory, we construct the HA structure for linguistic variables and use the SQMs function to convert each fuzzy point to a real point in the semantic space $[0,1]^{\mathrm{m}+1}$. Then, (Eq. 1) is represented respectively as a real "hyper-surface" $\mathrm{S}^{\mathrm{m}+1}_{\mathrm{real}}$. It is likely to consider the real "hyper-surface" $\mathrm{S}^{\mathrm{m}+1}_{\mathrm{real}}$ as the mathematical representation of the LRBS in which each fuzzy (linguistic value) of the fuzzy variable (linguistic variable) has been quantified into their semantic values (QRBS - Quantified Rule Base System).

Suppose that real inputs belong to the corresponding base space, the input values of the controller $\mathrm{x}_{01}, \mathrm{x}_{02}, \ldots, \mathrm{x}_{0\mathrm{m}}$, use the normalization of those values in the value domain of HA we have $\mathrm{x}_{01\mathrm{s}}, \mathrm{x}_{02\mathrm{s}}, \ldots, \mathrm{x}_{0\mathrm{ms}}$respectively. The approximation reasoning problem is carried on by the interpolation method on $\mathrm{S}^{\mathrm{m}+1}_{\mathrm{real}}$. The interpolation value received in the domain $[0,1]$ is the quantitative semantic value of the output linguistic variable $\mathcal{Y}$ that is transferred to the real variable domain (base space of the $\mathcal{Y}$ variable) of the output control value by denormalization.

The model of the controller based on HA approaching is described in Fig. 1.

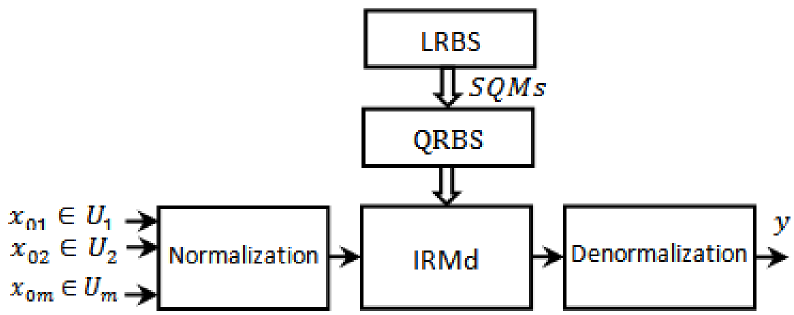

Fig. 1 Controller's diagram based on HA approach

In Fig. 1, the components are included:

LRBS: Linguistic Rule Base System of the controller.

QRBS: Quantifying rule based system of linguistic values which is computed by mapping function SQM ($\mathrm{S}^{\mathrm{m}+1}_{\mathrm{read}}$).

Normalization: standardize values of the variables in the semantic domain.

IRMd (Interpolation Reasoning Method): Interpolation on the "hyper-surface" $\mathrm{S}^{\mathrm{m}+1}_{\mathrm{real}}$.

Denormalization: convert semantic control value to the domain of variable real value of the output variable.

Steps of designing the controller based on hedge algebra as follows:

Step 1: Identify I/O variables, their variation domains, and control rules with linguistic elements in HA.

Step 2: Select the structure $\mathcal{AX}_\mathrm{i}$, $(\mathrm{i} = 1,..,\mathrm{m})$ and $\mathcal{AY}$ for variables $\mathcal{X}_\mathrm{i}$ and $\mathcal{Y}$. Determine the fuzzy parameter of generating elements, hedges and the sign relationship between the hedges.

Step 3: Compute quantitative semantic values for linguistic labels in the rule set. Construct the "hyper-surface" $\mathrm{S}^{\mathrm{m}+1}_{\mathrm{real}}$.

Step 4: Select the interpolation method on the "hyper-surface" $\mathrm{S}^{\mathrm{m}+1}_{\mathrm{real}}$.

Step 5: Optimize the parameters of the controller base on Genetic Algorithm (GA)

Genetic Algorithm (GA) is a method which finds solutions randomly for overall structure based on the process of natural evolution. Genetic Algorithms are part of the broader class of evolutionary algorithms. Genetic Algorithms imitate the same mechanisms as those found in nature (including reproduction, breeding and mutation) to find the best solution [2].

By starting at some independent and parallel search points, GA avoids extreme local extremes as well as convergence to secondary optimization solutions. As a result, GA has been shown to be able to locate high performance areas in complex spaces without the hassles involved in the dimension of space such as gradient techniques or optimization search methods based on information about derivatives.

GA enforcement is usually initiated with a random population of 50 to several hundred individuals, depending on the problem. Each individual is an optimal set of parameters, usually represented by a real or binary number

sequence and is called a chromosome. Each parameter corresponds to a segment of the chromosome, called the gene. Replication and mutation processes occur randomly to exchange and transfer information of genes. Adaptation of the next generations always inherits the adaptation of the previous generation.
The assessment of an individual's adaptation is measured by a finess function, called the finess value. Normally, in optimization problems, the optimal goal is to minimize the target function. Through long-term evolution and selection, adaptation to natural processes, individuals will gradually adapt to the objective function. Correspondingly, each instance will be an optimal set of asymptotic parameters by fitness function. Here, the fitness function is calculated according to the IAE (Integrated of The Absolute Magnitude of the Error). The control system model is often modeled on a discrete domain over time, so the IAE standard is transformed into the below form:

$$\mathrm{fitness} = \sum_{k=1}^{l} |e(k)| \rightarrow \min \qquad \text{(Eq. 2)}$$

Where: $e(k) = x_d(k) - y(k)$ is the sample deviation at the kth simulation cycle, l is the total number of data samples of a simulation test. $x_d(k)$is the reference value at the input, in many mathematical problem this is a constant. $y(k)$is the true response value of the output on the control object.

III. DESIGNING THE TEMPERATURE CONTROLLER OF SLAB

3.1 The mathematical model of the slab

Heating equipment is an equipment which is widely used in industry, medical and civil. In the industry, it is often used in heat treatment, melting ferrous and non-ferrous metals. One requirement of heat treatment is that the temperature of the furnace must be controlled according to temperature of slab. There are two ways to control the temperature of the slab:
- Direct measurementmethod of the temperature of the slab: This method, if implemented, is high-precision control. However, in the reality, it is only possible to measure the surface temperature of the slab, it is impossible to measure the thermal distribution within the slab because it is impossible to place a temperature sensor within slab.
- Indirect measurementmethod of the temperature of the slab: This method calculates the temperature of the slab according to the heat transfer equations, and takes that as the basis for the control. Based on the temperature calculation model of the slab, it is possible to calculate the temperature of the surface of the slab and the heat distribution in the slab from the furnace temperature.
In this study, the authors used indirect measurementmethod of the temperature of the slab. To control the temperature of the slab, we need the temperature field model of the slab. Specifically, according to [6], consider a one-sided burning furnace for the thin slab as shown in Fig. 2

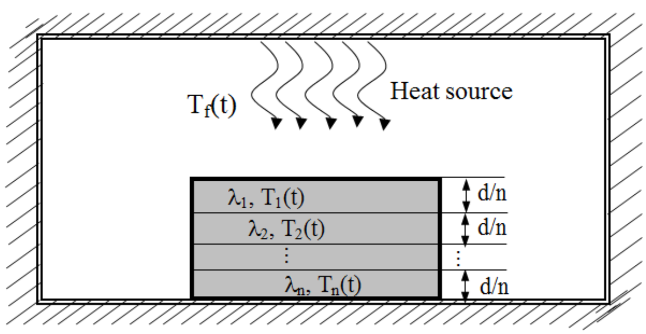

Fig 2. Thermoforming model of thin slab

The heat transfer in the furnace will consist of two steps:
Step 1: The heat energy of the furnace is transferred to the outer surface of the slab by radiation or convection heat transfer, in which case the radiant heat transfer is predominant, the convective heat transfer is secondary.
Step 2: Heat conduction from the outside to the inside of the slab
Considering the slab with the following parameters:
Thermal conductivity: $\lambda(\frac{W}{mK})$
Heat transfer coefficient: $\alpha\ (\frac{W}{m^2})$
Length: a (m)

Width: b (m)
Thickness: d (m)
Specific weight $\rho\ (\frac{Kg}{m^3})$
Specific heat $c\ (\frac{J}{kg.K})$
Surface area of the slab is $A = a.b(m^2)$
Assuming the volume of the furnace is small, the temperature in the furnaceis the same and the heat transfer through the head and sides of the slab is ignored, it is possible to divide the slab into n layers as shown in Fig 2.
According to Fig 2, we can consider that the temperature in the furnace is the input of the thermal conduction in the slab and the temperature of the bottom layer is the output of the thermal conduction in the slab, so that n layers of the slab can be described as the following transfer function [6]:

$$W_n(s) = \frac{1}{R_nC_ns+1}$$

$$W_{n-1}(s) = \frac{1}{1+R_{n-1}C_{n-1}s+\frac{R_{n-1}}{R_n}\big(1-W_n(s)\big)}$$

…

$$W_2(s) = \frac{1}{1+R_2C_2s+\frac{R_2}{R_3}\big(1-W_3(s)\big)}$$

$$W_1(s) = \frac{1}{1+R_1C_1s+\frac{R_1}{R_2}\big(1-W_2(s)\big)}$$

With $R_1 = {}^{1}/_{A\alpha}$;$R_2 = \frac{d/n}{\lambda_1 A}$;$R_3 = \frac{d/n}{\lambda_2 A}$;…; $R_n = \frac{d/n}{\lambda_{n-1} A}$
The value n is chosen according to the "thickness" of the slab and the accuracy requirementwhen describing the thermal conductivity in the slab.
In this study, the authors selected the slab with the following parameters:
Thermal conductivity: λ=55.8 $(\frac{W}{mK})$
Heat transfer coefficient: α= 335 (W/m^2)
Specific weight $\rho = 7800\ (\frac{Kg}{m^3})$
Specific heat $c = 460(\frac{J}{kg.K})$
Length: a= 0.5 (m)
Width: b= 0.4 (m)
Thickness: d= 0.05 (m)
Surface area of the slab is $A = a.b = 0.2\ (m2)$
In this study, we dividethe slab into 4 layers. We have the thickness of each layer is ${}^{d}/_{4} = 0.0125\ (m^2)$
The volume of each layer is $V_1 = V_2 = V_3 = V_4 = 0.5 * 0.4 * 0.0125 = 0.0025\ (m^3)$
The mass of each layer is $m_1 = m_2 = m_3 = m_4 = V_1 * \rho = 0.0025 * 7800 = 19.5$ (kg)

$$C_1 = C_1 = C_1 = C_1 = m_1 * c = 19.5 * 460 = 8970$$

$$R_1 = {}^{1}/_{A\alpha} = {}^{1}/_{0.2 * 335} = 0.0149$$

$$R_2 = R_3 = R_4 = \frac{d/n}{\lambda A} = {}^{0.0125}/_{55.8 * 0.2} = 0.00112$$

The transfer function of each layer is

$$W_4(s) = \frac{1}{R_4C_4s+1} = \frac{1}{10.05s+1}$$

$$W_3(s) = \frac{1}{1+R_3C_3s+\frac{R_3}{R_4}\big(1-W_4(s)\big)} = \frac{10.05s+1}{100.9s^2+30.14s+1}$$

$$W_2(s) = \frac{1}{1+R_2C_2s+\frac{R_2}{R_3}\big(1-W_3(s)\big)} = \frac{100.9s^2+30.14s+1}{1014s^3+504.7s^2+70.33s+1}$$

$$W_1(s) = \frac{1}{1+R_1C_1s+\frac{R_1}{R_2}\big(1-W_2(s)\big)} = \frac{1014s^3+504.7s^2+70.33s+1}{1.358.10^5s^4+8.21.10^4s^3+1.665.10^4s^2+1141s+1}$$

3.2 Hedge Algebras controller (HA controller)

The structure of the temperature control system of the slab is shown in Fig. 3

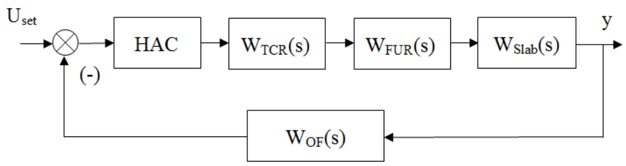

Fig. 3. The structure of the temperature control system of the slab

With transfer function of the thyristor-controlled transformer: $W_{TCR}(s) = \frac{22}{0.0033s+1}$ [6]

Transfer function of the resistor furnace: $W_{FUR}(s) = \frac{5e^{-30s}}{500s+1}$ [6].

The transfer function of output feedback $W_{OF}(s) = 0.01$ [6]

In order to control the temperature of the slab satisfies the requirements of the technology; the authors select the temperature control of the first layer of the slab according to the following structure diagram:

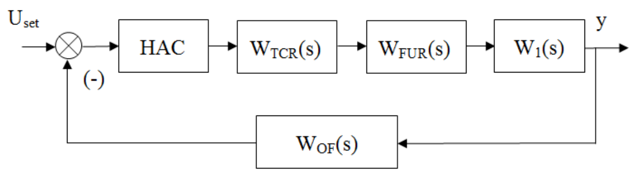

Fig. 4. The structure of the temperature control system of the slab

The design of the HA controller is implemented according to the steps presented in the previous section as follows:

Step 1: Identify input/output variables, their variation domains, and control rule set with linguistic elements in HA. The controller has 02 input

- e $(error)$ – control deviation, variation in the interval [-4, 4].
- ce $(changeerror)$ – indicates the variable rate of e in the range [-0.04, 0.04],
- Controller output is the control quantity u to control the voltage of the source, varying in the interval = [-150, 150].

The input/output linguistic variables include the following linguistic values:

- $e, ce = \{VN < LN < ZE < LP < VP\}$
- $u = \{VN < N < LN < ZE < LP < P < LP\}$.

Where:

$VN = VeryNegative, LN = LittleNegative, ZE = Zero, LP = LittlePositive, VP = VeryPositive.$

The control rule is considered to be an LRBS and presented as the following table:

Table 1 Control rule set

e \ ce	VN	LN	ZE	LP	VP
VN	VN	VN	N	LN	ZE
LN	VN	N	LN	ZE	LP
ZE	N	LN	ZE	LP	P
LP	LN	ZE	LP	P	VP
VP	ZE	LP	P	VP	VP

Step 2: Choose the structure of $\mathcal{AX}_i$, $(i = 1, .., m)$ and $\mathcal{AY}$ for the variables $\mathcal{X}_i$ and $\mathcal{Y}$. Identify the fuzzy parameter of the generating elements and the hedges

The set of generating elements $G = \{N < P\}$.

The set of hedges is chosen: $H^- = \{L\}$và $H^+ = \{V\}$.

The fuzzy parameter of hedge algebra gives the variable e, ce and u which include the fuzzy measurement of the generating elements, the fuzzy measurement of the hedges. According to the hedge algebraic structure for the variables constructed above, we need to choose the fuzzy measurement of the negative elements $fm(c^-) = fm(N)$ $(fm(c^+) = 1 - fm(c^-) = fm(P) = 1 - fm(N))$ the fuzzy measurement of the negative hedges $\alpha = \mu(L)$ $(\beta = \mu(V) = 1 - \alpha)$. The fuzzy parameters are initially chosen as intuitive as in Table 2.

Table 2. The fuzzy parameters of HA

	e	ce	u
$fm(N)$	0.50	0.50	0.50
$\alpha = \mu(L)$	0.50	0.50	0.50

The sign of the generating elements, hedges and sign relations between the hedges is determined by the semantic nature of the linguistic terms. For example, $sgn(N) = -1$, $sgn(P) = 1$. Moreover, it can be seen that $VVN < VN \Rightarrow sgn(V,V) = 1$. $LVN > VN \Rightarrow sgn(L,V) = -1$. In additions, it is similar to other linguistic elements, so we define the sign relation as in the Table 3.

Table 3. Sign relation

	V	L	N	P
V	$+$	$+$	$-$	$+$
L	$-$	$-$	$+$	$-$

Step 3: Compute quantitative semantic values for linguistic labels in the rules. Construct "hyper-surface" S^{m+1}_{real}.
Step 4: Select interpolation method: The interpolation method on S^{3}_{real} is chosen as bi-liner interpolation.
Step 5: Optimize fuzzy parameters of the controller
It can be seen that the variable domain of input/output variables is symmetric. The semantics of the linguistic element is zero by itself. When mapping to the semantic domain in the range [0,1], the semantic value $v(ZE) = 0.5$. Therefore, we stably choose for value variables, $fm(N) = 0.5$. We only need to optimize the fuzzy measurement of the hedges. The set of hedges in the hedge algebra is constructed by only two hedges, V (Very) and L (Little). We have: $\alpha = \mu(L)$ $(\beta = \mu(V) = 1 - \alpha)$. Therefore, we just need to optimize the fuzzy measurement of the negative hedges $\alpha = \mu(L)$, we will infer the fuzzy measurement of the positive hedges. We have 3 HA structures for 3 variables e, ce and u. Correspondingly, we have three parameters to optimize, alfa_e, alfa_ce and alfa_u. In theory, the fuzzy measurement can be varied from 0 to 1. However, in order to match the description of the language, we choose to search for the values of these parameters in the interval [0.3, 0.7].

In the Matlab environment, GA is an existing function as a tool that helps us to use it. In this study, we used the ga() function in Matlab with the gene code by the real number type double. The values set for GA include: Population size, PopulationSize = 150; Generation = 450. The target function is used as in formula (Eq. 2).
The result gained the set of parameters for the controller as shown in Table 4.

Table 4. Optimal parameters of the controller HAC based on GA

	e	ce	u
$\alpha = \mu(L)$	0.30185	0.391122	0.484335

Based on the optimal fuzzy parameters found in Table 4, we compute the quantitative semantic values of the linguistic classes of the rule table; we obtain the QRBS table of the optimal controller HA as shown in Table 6 and corresponding input/output relation surface in Fig. 5.

Table 5.QRBS of the optimal controller HA

e \ ce	0.2437	0.3491	0.5	0.6509	0.7563
0.1854	0.1411	0.1411	0.2737	0.4062	0.5307
0.3044	0.1411	0.2737	0.4062	0.5307	0.6408
0.5000	0.2737	0.4062	0.5307	0.6408	0.7580
0.6956	0.4062	0.5307	0.6408	0.7580	0.8752
0.8146	0.5307	0.6408	0.7580	0.8752	0.8752

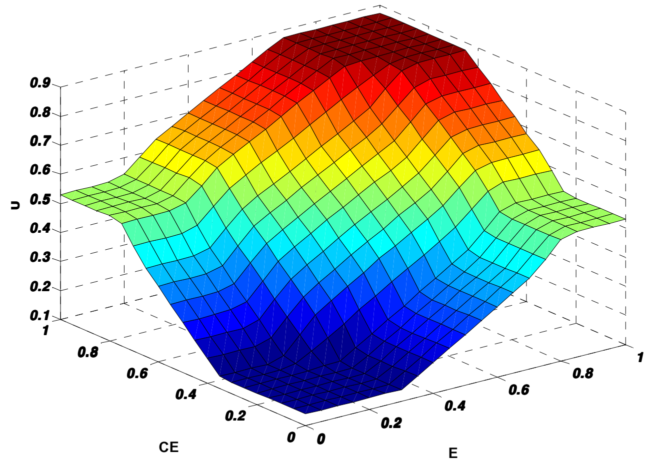

Fig. 5. The input/output relation surface S^3_{real} of the optimal controller HA

IV. SIMULATION RESULTS

Using the HA controller to control the slab temperature, we obtained the following results

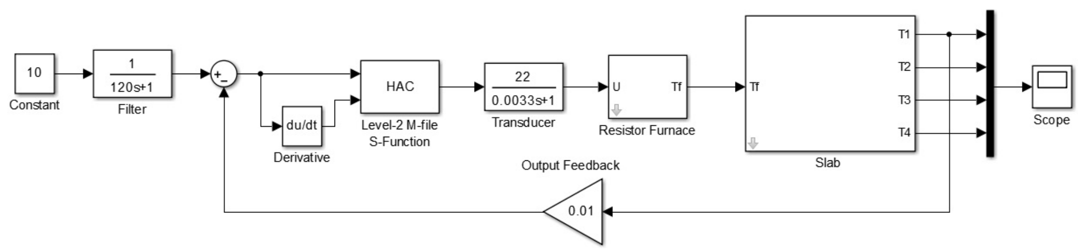

Fig. 6. Simulink Diagram for System Simulation

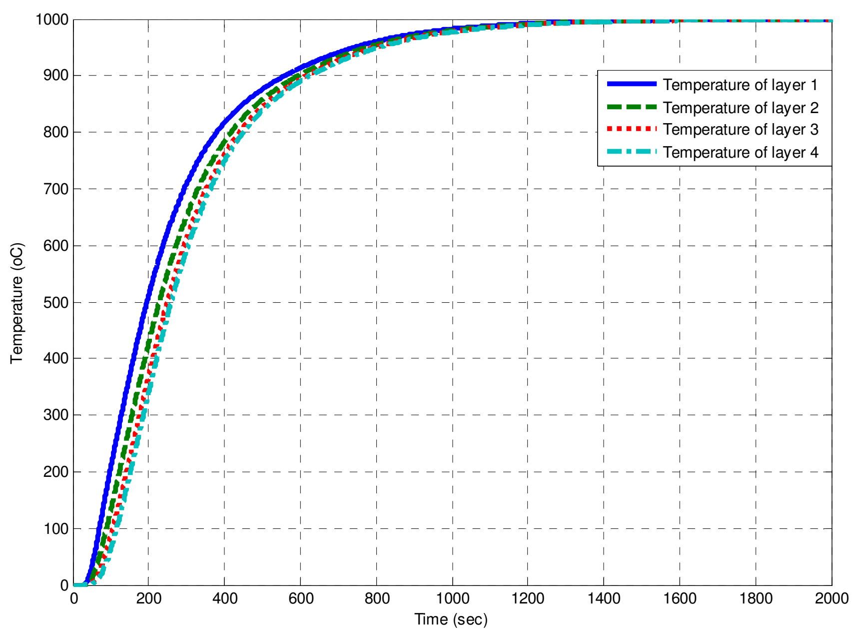

Fig.7. Graphical response of the System

Comment: Based on the simulation results, we find that

- Rise Time: 810s

- Overshoot: 0%
- Static deviation $S_t = 0\%$
- Without overadjustment.

After 1400s, the temperature of the four layers of the slab reached almost the same level.

Thus, using the HA controller we can control the temperature of the slab to reach the desired temperature (set temperature) with static deviation $S_t = 0\%$, without overadjustment.

V. CONCLUSION

The paper presents a method of designing the algebraic controller and application of the HA controller to control the temperature of the slab that mentioning the optimization of the controller parameters. According to this approach, the representative structure of the LRBS is very tight, the number of computations is not much, so it can perfectly response to systems that require real-time response. The controller has just a few parameters so it is also convenient to optimize. To optimize the controller effectively, we use GA. The simulation results show the correctness of the mathematical form of the transfer function of the slab and the controller HA. To test the practical applicability of this study we need to experiment on the real model that the results of this study will have very high practical significance.

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