Robust control design for heating section of insulation testing machine

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Abstract

An insulation testing apparatus consists a two-zone temperature system, i.e. the heating section and the cooling section, to generate temperature difference situation between the insulation materials, according to ISO 8301: the thermal resistant testing standard for insulation materials. These works focus in studying and controlling the dynamic performance of the heating section in order to accurately and efficiently manage its temperature. Hence, the accuracy of the testing result can be improved. The initial observation found that the heating part is considered as an uncertain system, of which is related parameters can be varied depending on the operating condition and the conventional control strategy such as, PID control cannot effectively handle this variation. This study discusses the design and implementation of the temperature control of the heating section using robust control strategies, i.e. H_∞ controls and compared with the conventional PID control. The results show that the transient behavior of the system using the proposed method is improved as compared to that of the PID control. The steady-state behaviors, on the other hand, are similar and in an acceptable range.

Keywords: H_∞ control, Heater control, ISO 8301

1. Introduction

Thermal resistant of construction material is a benefit for representation the ability to slow down the heat energy from the outside to the inside area, for example, heat radiation for ambient air transfer thought building material to the air condition room. If building material has more value of thermal resistant that material can hold and slow down the heat energy from outside to inside.

Therefore, the energy consumption of air condition system inside a room can be reduced by using high thermal resistant material for building part of room area.

The insulation material is a one of high thermal resistant for reducing the rate of energy transfer and this material has a standard for testing thermal resistant following ISO 8301[1].

The testing apparatus consists main two pieces of thermal zone's order for simulate different temperature condition between testing material. The first part is cooling plate for generation low source temperature, and the second part is a hot plate for creation high temperature area. In addition, sample for testing is place between two difference plate temperatures for simulation the energy transfer condition as shown in Fig.1.

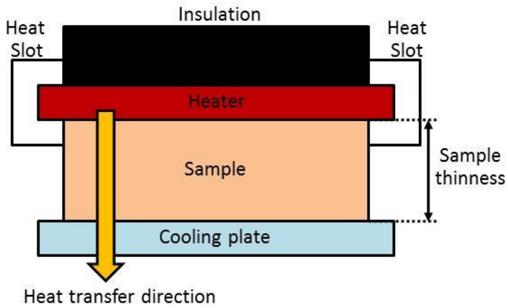

Fig. 1 Insulation testing machine

The central points of testing apparatus are control temperature of two plates thermal system for the specification the steady-state condition for sample and in this work is focused on develop a control algorithm of a heater section of insulation testing machine.

Heater equipment is a kind of first order system. Therefore, many literatures focus on control of the first order system such as, electrical water heater system, hot-air system and heater plate.

Several techniques have been proposed in the literature for controlling temperature of a heater element in different application.

In [2-4] have proposed the hybrid controller, such as fuzzy controller plus PID, immune controller plus PD for dueling with system uncertainty in a heater element.

In [5] has proposed the model structure strategy for adopting the control effort for handling the variation of system parameters due to operating condition in a heater element.

From the literature, many researchers were developed control algorithms to deal with plant uncertainty of the system and ability to reject a disturbance. As a result, robust controller should be implemented because this algorithm has the ability to duel with model uncertainty.

The proposed H_∞ control strategy is verified by both of simulation and experiment. A comparison study between H_∞ control and conventional PID control based on control performance and robustness.

2. Hardware setup

The test section is contain many equipment, for example, solid state relay used to distribute one phase electrical power when control signal from data acquisition (NI-USB 6009) is applied to solid state relay in a finite time, heater 1000 watt use for generating output temperature of insulation apparatus, thermocouple and heat flux sensor for logging data section and analog signal of the temperature can be amplifier by thermocouple amplifier circuit. The amplified of a temperature signal is used to feedback data for calculation of an error signal in the controller section. In this study, Lab View software, which is graphical software for calculation the process of the algorithm, used to study different control algorithm such as, PID, LQR and H_∞ in heater system. The block diagram of each equipment can be seen in Fig. 2.

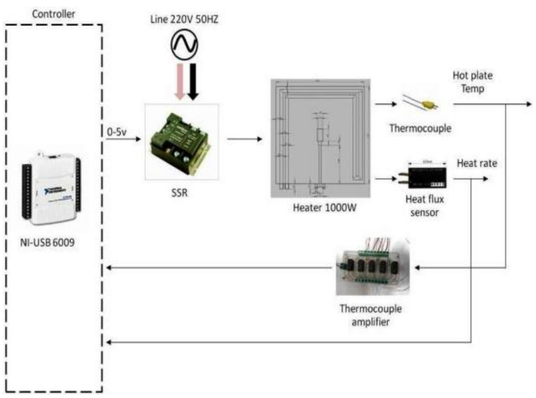

Fig. 2 Block diagram of hardware and software configuration.

3. System modeling

This work use conservation of energy for developing system model.

3.1 Nominal modeling

The heater is an aluminum resistant heater, which is an element to transform electric energy to heat energy as shown in Fig. 3. The derivation of a mathematic plant model can be determined by conservation of energy law between heater boundaries as

$$\frac{dT}{dt} + \frac{1}{RC}T = \frac{1}{C}q_{in} + \frac{1}{RC}T_{amb} \quad (1)$$

The related notations are:

T Surface temperature of the heater unit in $(°\mathrm{C})$

T_{amb} Ambient temperature of surrounding unit in $(°\mathrm{C})$

R Thermal resistant of heater unit in $(°\mathrm{C}/W)$

C Thermal capacitance of heater unit in (J/K)

q_{in} Electrical power input to heater (W)

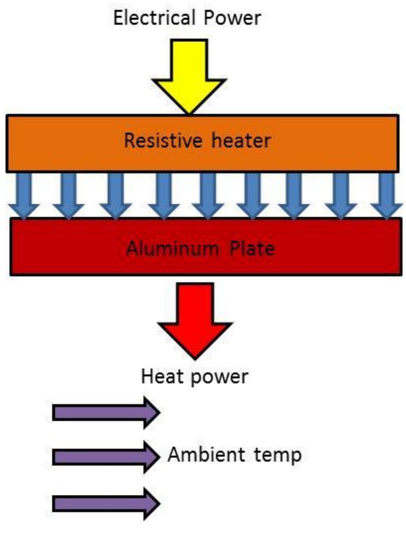

Fig. 3 Resistive heater system.

The state-space representation of a nominal plant can be derived from Eq. (1) and can be shown in Eq. (2).

$$\begin{cases} \dot{x}_p = A_n x + B_{nd} d + B_{nu} u \\ y = C_n x_p \end{cases} \quad (2)$$

Where the state-space vectors are $x_p = [T], x = [T], d = [T_{amb}], u = [q_{in}]$ and the state-space matrix are $A_n = \left[-\frac{1}{\tau}\right], B_{nd} = \left[\frac{1}{\tau}\right], B_{nu} = [K], C_n = [1]$ when parameter $\tau = RC$ and $K = \frac{1}{C}$, the plant matrices are set of working condition, when the set $(\Omega)$are

$$\left\{ \begin{bmatrix} A_1 & B_{d_1} & B_{u_1} \\ C_1 & 0 & 0 \end{bmatrix}, \ldots, \begin{bmatrix} A_N & B_{d_N} & B_{u_N} \\ C_N & 0 & 0 \end{bmatrix} \right\} \quad (3)$$

Therefore, nominal plant matrices can be calculated by Eqs. (4) – (7).

$$A_n = \frac{\sum_{i=1}^{N} A_i}{N} \quad (4)$$

$$B_{nd} = \frac{\sum_{i=1}^{N} B_{d_i}}{N} \quad (5)$$

$$B_{nu} = \frac{\sum_{i=1}^{N} B_{u_i}}{N} \quad (6)$$

$$C_n = \frac{\sum_{i=1}^{N} C_i}{N} \quad (7)$$

When N is a total number of operating condition of the system and matrix in i state, is plant parameters on working condition$i$. The plant parameters of heater system are varying due to operate at different working condition. The essential parameters of heater system can be extracted from open-loop experimental by system identification such as, least square algorithm, open-loop step test at every working condition.

3.1 Parameters estimation with least square algorithm

Essential parameters of the system can be determined by least square algorithm, which is a process to find unknown parameters from a physical model; the least square method can be written as

$$Y = \Phi\theta \tag{8}$$

Where

θ is an unknown parameter vector, such as model parameter.

Φ is known regression matrix, which is the matrix contain a data of state and input, from experiment condition.

Y is known measurements vector, such as output of the system.

The solution of θ can be found from Eq. (9).

$$\theta = \Phi^{-1}Y \tag{9}$$

The solution of least square for $Y = \Phi\theta$ can be written as

$$\theta_{LS} = (\Phi^T\Phi)^{-1}\Phi^T Y \tag{10}$$

Mathematic model can be rewritten in the form of least square algorithm as

$$\underbrace{\dot{T}}_{Y} = \underbrace{[T \quad q_{in}]}_{\varphi}\underbrace{\begin{bmatrix}-\frac{1}{\tau}\\ K\end{bmatrix}}_{\theta} \tag{11}$$

In order to find θ using least square algorithm this method need to log input and output data. Therefore, this system will be discrete and apply Euler forward method to differential term as

$$\underbrace{\frac{T_{k+1}-T_k}{T_s}}_{Y} = \underbrace{[T \quad q_{in}]}_{\varphi}\underbrace{\begin{bmatrix}-\frac{1}{\tau}\\ K\end{bmatrix}}_{\theta} \tag{12}$$

Where T_s is the sampling time of logging data. This work set sampling time equal to $1ms$. The open-loop test is use to identifier two essential parameters as shown in Fig. 4. The identifier process use input signal condition as impulse signal in several time condition to heater system, then recorded output temperature signal. Each plant parameter can be extracted by identification process and plant parameters are varying due to working condition as shown in Table. 1.

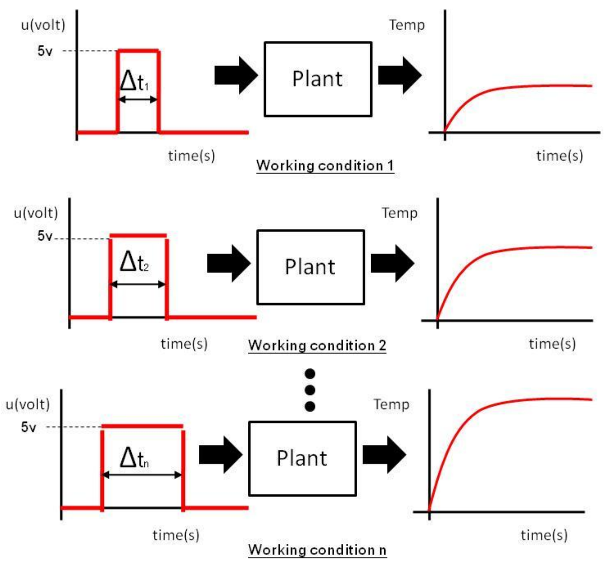

Fig. 4 Working condition for each identifier process

The heater plate is one kind of thermal inertia system, which is the system still working when input signal equal to zero in a finite time, As a result, the unit step function cannot use as an input signal for this system because the output temperature of heater plate does not tend to steady-state values and every magnitude of the step function.

Table. 1 plant parameters for each working condition

Input condition		Plant parameters	
Working condition i	Δt_i (s)	K	τ
1	100	10.2	175
2	200	15.8	193
3	300	14.2	187
4	400	17.1	194
5	500	18.9	205
Nominal parameters		15.2	191

Therefore, nominal model can be written as

$$G_N = \frac{15.286}{190.8S+1} \tag{13}$$

3.2 Plant modeling with uncertainty

Uncertainties arise from numerous source, for example, measurements part for a feedback signal, environment condition and operating condition. The plant parameters will be uncertain as shown in Fig. 5.

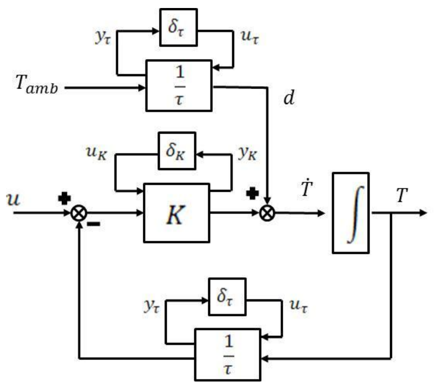

Fig. 5 Block diagram of heater system with uncertain parameter.

The variation of steady-state gain parameters (K) and time constant parameters (τ) can been seen in Fig. 6 and 7, respectively.

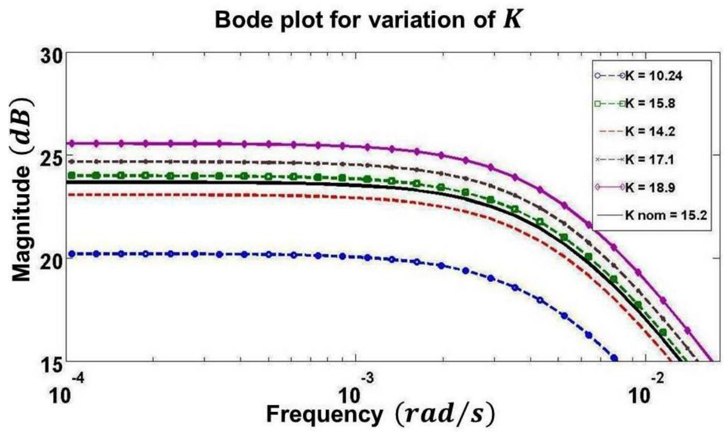

Fig. 6 Variation of steady-state gain in bode plot solid line is nominal parameter.

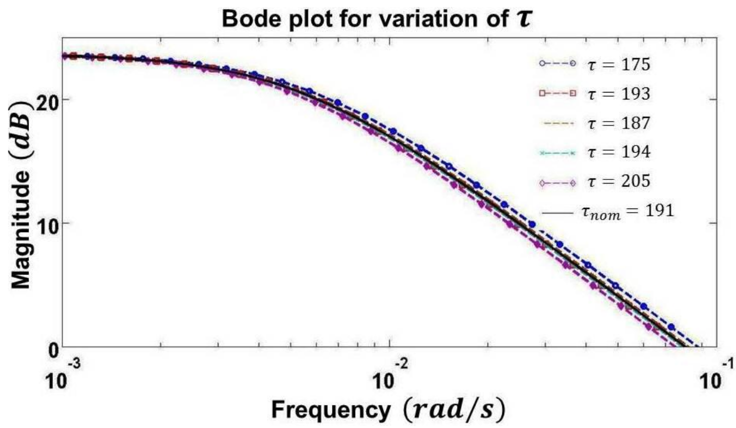

Fig. 7 Variation of time constant in bode plot solid line is nominal parameter.

From Fig. 5,parameters in heater system are represented in term of parametric uncertainties, which is parameters in heater system be composed of nominal part and uncertain counterpart, as shown in Eq. (14) and (15), for steady-state gain and time constant parameter, respectively.

$$K = \bar{K}(1 + P_K\delta_K) \qquad (14)$$

$$\tau = \bar{\tau}(1 + P_\tau\delta_\tau) \qquad (15)$$

Where $\bar{K}$, $\bar{\tau}$ stand for nominal parameters, P_K, P_τ are represent to parameter variation bound, and δ_K, δ_τ are specific parameter variation within the bound specified by δ_K and δ_τ, respectively. The state space equation of heater as shown in Eq. (2) need to be reformulated based on the related parametric uncertainties as shown in Eq. (16) and expansion in two parts of nominal part and uncertain part as

$$\dot{T} = -\frac{1}{\bar{\tau}(1 + P_\tau\delta_\tau)}T + \frac{1}{\bar{\tau}(1 + P_\tau\delta_\tau)}T_{amb} + \bar{K}(1 + P_K\delta_K)u \qquad (16)$$

$$\dot{T} = \underbrace{-\frac{1}{\bar{\tau}}T + \frac{1}{\bar{\tau}}T_{amb} + \bar{K}u}_{nominal\ part} + \underbrace{u_\Delta^1 + u_\Delta^2 + u_\Delta^3}_{uncertain\ part} \qquad (17)$$

All uncertain part of Eq. (17) can be written as Eqs. (18) – (20) for u_Δ^1, u_Δ^2 and u_Δ^3, respectively.

$$u_\Delta^1 = \frac{P_\tau\delta_\tau}{\bar{\tau}(1+P_\tau\delta_\tau)}T \qquad (18)$$

$$u_\Delta^2 = -\frac{P_\tau\delta_\tau}{\bar{\tau}(1+P_\tau\delta_\tau)}T_{amb} \qquad (19)$$

$$u_\Delta^3 = \bar{K}P_K\delta_K u \qquad (20)$$

4. Controller design

This work using the mix-sensitivity approach to duel with system uncertain. The $S/KS/T$ mixed sensitivity problem use in generalized plant as shown in Fig. 8. The expression of the resulting closed-loop transfer function, $T_{zw}(S)$, is as

$$T_{zw}(S) = \begin{bmatrix} W_S(s)S_o(s) \\ W_{KS}(s)K(s)S_o(s) \\ W_T(s)T_o(s) \end{bmatrix} \qquad (21)$$

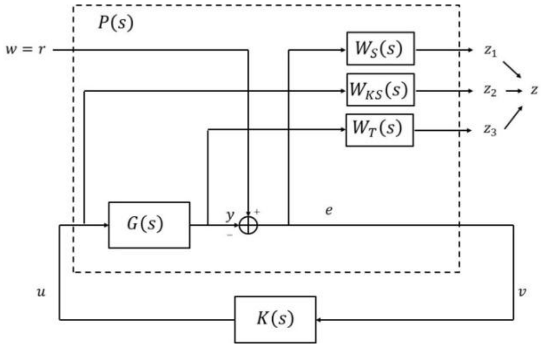

Fig. 8 $S/KS/T$ mixed sensitivity.

Where $S_o(s)$ is the output sensitivity transfer function matrix, $T_o(s)$ is the output complementary sensitivity transfer function matrix, and $K(s)S_o(s)$ is the control sensitivity transfer matrix. The equation of each sensitivity transfer function matrix can be written by Eqs. (22) – (24), respectively.

$$S_o(s) = \big(I + G(s)K(s)\big)^{-1} \qquad (22)$$

$$T_o(s) = G(s)K(s)\big(I + G(s)K(s)\big)^{-1} \qquad (23)$$

$$K(s)S_o(s) = K(s)\big(I + G(s)K(s)\big)^{-1} \qquad (24)$$

$W_T(s)$ should be as upper bound of the maximum singular values of the multiplicative output uncertainty as

$$\Delta_i(s) = \left(\hat{G}_{Pi}(s) - \hat{G}(s)\right)\hat{G}(s)^{-1} \qquad (25)$$

When $\hat{G}(s)$ is nominal model and $\hat{G}_i(s)$ is each of non-nominal model from working condition. Fig. 9 shows the maximum singular values of each non-nominal working condition.

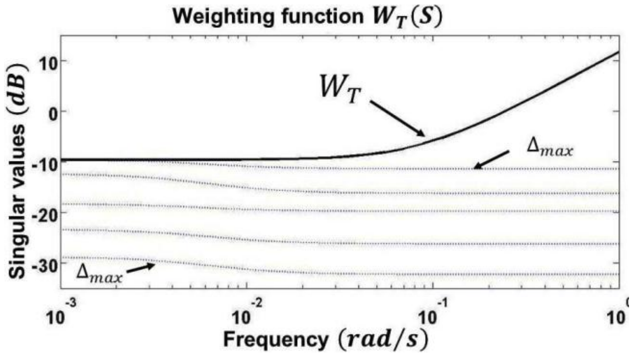

Fig. 9 $W_T(s)$ (solid line) as an upper bound of each maximum singular values of multiplicative output uncertainty (dot line).

This work use $W_T(s)$ function as

$$W_T(s) = \rho \frac{1.4s+0.12}{0.014s+0.12} \quad (26)$$

Where $\rho = 0.35$ and crossover frequency is 0.03rad/s, also the weight $W_S(s)$ according to design rules [11] can be choose as

$$W_S(s) = \frac{\alpha s + 10^{(\kappa-1)}\omega_T}{s+\beta 10^{(\kappa-1)}\omega_T} \quad (27)$$

When ω_T is a cross over frequency, parameters α and β are represent the transfer function gain at high and low frequency and dimensionless parameter κ use for tune speed of response.

The invert of the weight function $W_T(s)$ and $W_S(s)$ should be bound of sensitivity function of $T_o(s)$ and $S_o(s)$, respectively. Fig. 10 shows the upper bound of each sensitivity function.

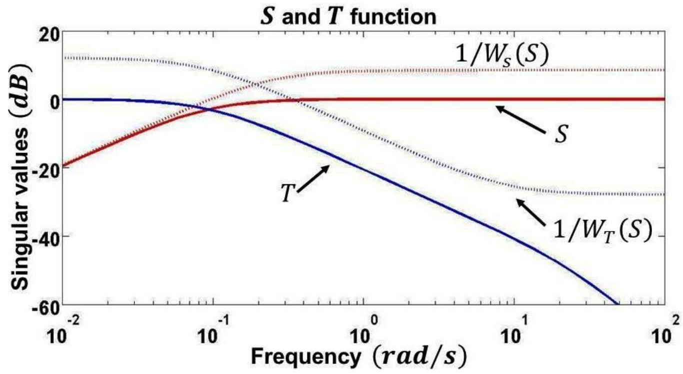

Fig. 10 Weight function (dash-line) as an upper bound of sensitivity function of $T_o(s)$ and $S_o(s)$ (solid line).

5. Simulation study

This work using Mat Lab program for studying performance of difference controller between robust H_∞ and conventional PID controller by simulation. This study is included disturbance to process for studying the ability to handle the effect of perturbation and $G_d(s)$ stand for disturbance transfer function as

$$G_d(s) = \frac{2}{10s+1} \quad (28)$$

The disturbance signal is chosen to sin function for a simulation study as shown in Fig. 11.

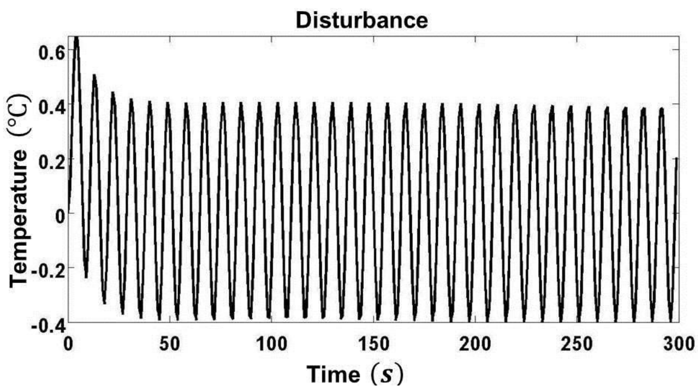

Fig. 11 Disturbance signal of a temperature.

5.1 Tracking performance

In this section, tracking ability of difference controller have studied by simulation as shown in Fig. 12. The line graph shows the tracking performance of H_∞ and PID controller. Overall it clear, transient behavior of PID controller is faster than H_∞, but this algorithm has a lagre overshoot when reference signal has been changed to other working conditions. In addition, steady-state error of two control algorithms are similarly.

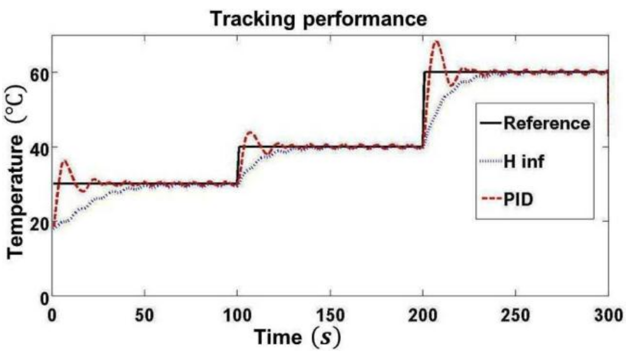

Fig. 12 Tracking performance of PID controller (dash-line) and H_∞ controller (dot line).

5.2 Control efforts study

In this section, this work focus on control effort,which is a voltage signal from the controller for driving heater to design temperature, by simulation study as shown in Fig. 13. Over all it clearly, controls effort level of H_∞ controller is near to zero voltage, which is not action in positive and negative direction to the system, than PID controller. In addition ,when reference signal has been changed to other working conditions the peak of H_∞ smaller than conventional PID controller.

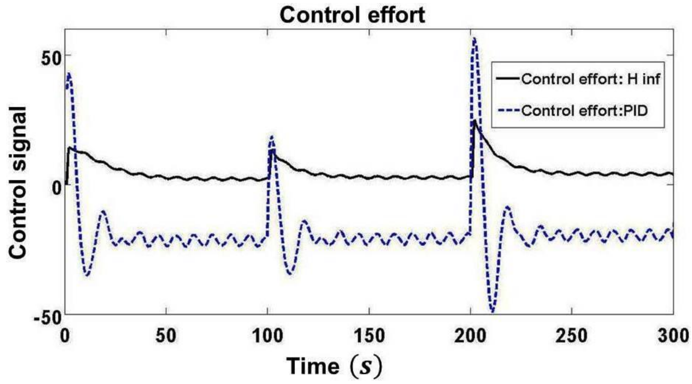

Fig. 13 Control effort of PID controller (dash-line) and H_∞ controller (solid line).

6. Experimental study

The experiment has tested about control performance of a heater section in insulation testing apparatus as shown in Fig. 14.

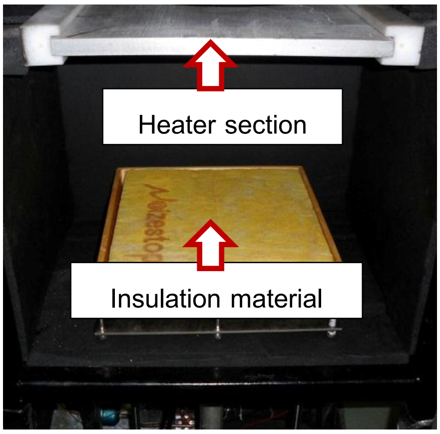

Fig. 14 An insulation testing apparatus

This experiment focus on control of temperature in a heater part for the testing controller ability. This work uses two working condition to verify performance of difference control algorithms in term of tracking reference, disturbance rejection, rising time and steady–state error. Fig 15 shows tracking performance of controllers.

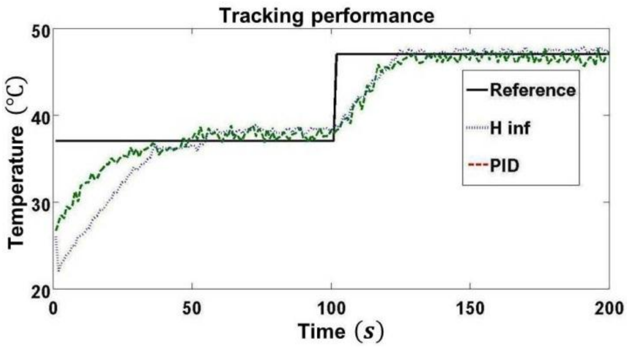

Fig. 15 Experiment result of PID controller (dash-line) and H_∞ controller (dot line).

From experiment result, the performances of two controllers are same in the term of rise time, but the robust H_∞ controller can be handled the disturbance caused by ambient temperature better than conventional PID controller.

7. Conclusion

The study on control performance of a heater section in an insulation testing apparatus has proposed in this work. For dueling with system uncertainty, this work uses robust control strategy for handling the effect of uncertainty and disturbance.

From simulation and experiment result have shown the effective of the robust controller for tracking reference signal and reject disturbance is better than using conventional PID controller.

8. Acknowledgement

Center for Energy Research and Testing Laboratory (CERT Lab), Department of Mechanical Engineering Mahidol University, 25/25 , Phutthamonthon sai 4 Road, Salaya, Phutthamonthon, Nakron phatom,73170.

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