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Industrial Temperature PID Controller for Pb-Free Soldering Iron ⋆

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Abstract: This paper presents a Pb-free soldering iron temperature controller in consideration of the use of an embedded micro-processor (MPU) with a low memory capacity. The proposed method is suitable for a wide use type commercial controller due to only a variable set point is applied to a PID controller. The proposed controller could solve the Pb-free soldering problem. The proposed method could be successfully applied to a commercial digital temperature controller.The controller has been commercialized.

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1. INTRODUCTION

Recently, much importance has been added to the environmental problem. The major content of two directives to better control the management of waste electronic equipment was approved. The two directives are the Waste from Electrical and Electronic Equipment (WEEE) and the Restriction of Hazardous Substances (RoHS). These set phase-out dates for the use of Pb (lead) materials contained in electronic products. Increasingly, the attention is focusing on the potential use of Pb-free soldering in electronics manufacturing. It should be noted that many of the conventional soldering irons are not suitable for Pb-free technology, due to the inferior ability of Pb-free alloys compared with SnPb solder pastes. This paper presents a Pb-free soldering iron temperature controller in consideration of the use of an embedded micro-processor (MPU) with a low memory capacity.

The temperature of soldering iron takes an important role in the fusing point of Pb-free solder. The soldering with Pb-free solder can be undertaken in every soldering iron which is able to produce sufficient heat, but it is important to ensure that the temperature does not overheat the components or the printed circuit board. The soldering iron is a time varying process depending on the soldering condition. Hence, it is difficult to compensate the excessive control input which causes the overheating. And also, due to the memory capacity of an embedded MPU is low to minimize the cost of controller, the advanced control theory cannot be acceptable. In this paper,the above soldering iron characteristics and the memory size are considered to design the temperature control system.

The easy design procedure for an embedded MPU with a low memory capacity in a soldering iron temperature control system is basically developed for the above problem of soldering. This paper proposed three methods based on bumpless and conditioned transfer techniques for the soldering technology. The topic of anti-windup and bumpless transfer has been studied by many researchers, the detail techniques are described in (Åström and Rundqwist (1989); Glattfelder and Schaufelberger (1983); Hanus et al. (1987); Peng et al. (1996)). First, a basic concept is shown based on a condition transfer technic using a virtual output limiter to constrain an integrator and a derivative for a PID regulator. And also, an integrator is initialized according to the discontinuous action of the output limiter. Secondary, a condition transfer plus bumpless method is proposed to reduce the program memory for the integrator rest code. Finally, the constrained input method by a variable set point is proposed. The variable set point is applied to the controller instead of a conventional setpoint. In this case, the nonlinearity is hidden in the variable set point. The advantage of proposed method is that the conventional PID control loop can be remained in the proposed procedure. The variable setpoint is only introduced to the computer code for a low memory MPU.The proposed controller has been commercialized.

2. PB FREE SOLDERING PROBLEMS

2.1 Pb-free soldering

The following characteristics of solder have changed compared with Pb solder.

- the high melting point
- the ball spattering
- the poor wettability
- the uneven brightness

These characteristic changes influenced all elements of the solder technology, such as the quality assurance, the cost and the maintenance. Table.1 shows the Pb-free soldering problems. Due to the high melting point, the complicated intermetallic compound and the poor wettability, Pb-free soldering needs the technical skills and the temperature monitoring. Consequentially, the development of a digital controller that specializes in the Pb-free technology is required to solve the problems.

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Fig. 1. Commercial Digital Temperature Controller TOHO ELECTRONICS Inc. TTM-000 series. (All experiments are performed by a Flash memory version of TTM-000.)

Table 1. The Pb-free soldering problems

	Problem	Main cause
Quality	Deterioration of fillet formation	Low heating, Poor wettability
	Poor contact	Low heating
	Ball spattering	High temperature
	Thermal breakdown	High temperature
Compensation	Difficulties of inspection	Uneven brightness Poor Controller
Repair	Bad working efficiency	Low heating Poor wettability
	Beyond repair	Low heating
Soldering iron	Perforation	High temperature
	Low oxidation	Poor wettability
	Carbonization	High temperature
Cost	Iron cost	Complicated functions
	Tact time	Low heating
	Parts changes	High temperature
	Maintenance cost	Substandard products

2.2 The Problem of temperature control

For Pb-free soldering iron, the temperature control problems are as follows:

- The excessive heater input

A control input is an excessive heater so as not to become the heat shortage through the connection with the printed circuits. The excessive input causes overheating.

- Time variant system

The controlled system is a soldering iron which has a small thermal capacity. However, the iron is a time-variant system when the iron contact with printed circuits or solder. The thermal capacity of printed circuits and solder cannot be predicted. It is possible to make four different contact combinations. And also the state changes are different when the solder is liquid or solid.

- Reduction in tact time

The overshoot have to be avoided after soldering. This leads a log settling time and a long waiting time. When the controlled system is only the iron, the overshoot causes frequently due to the thermal capacity of iron is small.

- Consideration of melting point

The melting point is raised 30°C $\sim$ 40°C compared with Pb soldering. The set point of the iron temperature is also raised. The proper heating temperature plus 40°C $\sim$ 50°C for the intermetallic compound.

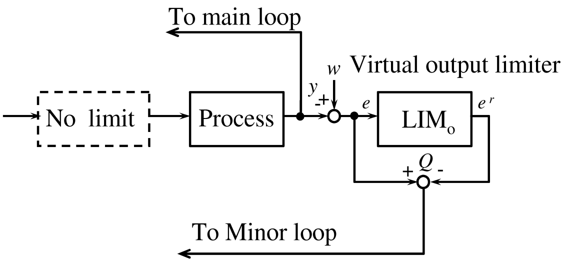

Fig. 2. The concept of proposed methods

- Restriction of MPU perfomance

The memory capacity of an embedded MPU is low to minimize the cost of controller. The advanced control theory (e.g. Hamane and Seborg (2002)) and the power phase control unit cannot be acceptable. And also, a sampling time of the controller is long due to a commercial AC power is used for the control input.

2.3 Control specifications

From the above restrictions, the control software redesign is required without hardware changes. The controlled system detects a temperature by a thermo-couple at the tip of iron. The temperature is fed back into the temperature adjustment circuit. And then the heater input is controlled by PID control. PID controller is parallel connected type (Åström and Hägglund (1995)),

$$
\begin{aligned}
U &= pmv + imv - dmv, \qquad (1)\\
\text{where} \quad pmv &= K(bW - Y),\\
imv &= \frac{K_i}{s}E,\\
dmv &= \frac{sK_d}{1 + sK_d/(NK)}(Y - cW),
\end{aligned}
$$

where: U, Y and W are Laplace transformations of the heater input (The heater watt is normalized by the definition of proportional band.), the temperature output and the setpoint, respectively. K is the proportional gain, K_i is the integration coefficient and K_d is the derivative coefficient. $b \in [0, 1]$ is the two degree of freedom coefficient and $c \in [0, 1]$ is the derivative tuning coefficient. $N \in [8, 20]$ is tuned to reduce the noise amplification. In this paper, $b = 1$, $c = 0$ are used for all experiments.

3. BASIC PROPOSED METHOD

3.1 Concept of proposed method

An excessive control input and the time-varying system have to be considered in the control system design. This controlled system does not cause a wind-up phenomenon (Seborg et al. (1989); Shinskey (1996)) due to the excessive control input removes a input limiter. Even if the anti windup techniques are applied, the overshoot cannot be removed. If the control algorism has the stop of an integral calculation, the temperature of a soldering iron will reach the unexpected equilibrium due to the small thermal capacity.

The main concept is using a virtual output limiter to constrain an integrator and a derivative for a PID controller.

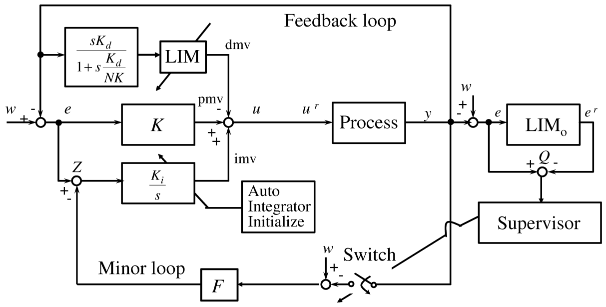

Fig. 3. Proposed method 1: Conditioned transfer type

An integrator constraint is considered for the small thermal capacity of iron. A derivative constraint is to eliminate the noise influences of an excessive control input and time-variable system. The concept of proposed method is shown in Fig.1. The input limiter does not exist in this controlled system. On the other hand, the proposed method has a virtual output limiter $\mathrm{LIM_o}$:

$$e^r = \begin{cases} H_L & ; e > H_L \\ e & ; -H_L \leq e \leq H_L \\ -H_L & ; e < -H_L \end{cases}, \tag{2}$$

which works as a minor loop to operate an integrator and a derivative of PID controller. H_L is the band of limiter.

Note that u and u^r denote the controller output and the real process input, respectively. The real process input u^r is influenced by the nonlinearity of limiter or switching algorism. The values of u^r and u are different. e and e^r denote the real error and the error of output limiter, respectively.

3.2 Basic concept of the integrator action

Fig.3 shows a basic concept based on a condition transfer technic using a virtual output limiter. The supervisor operates the switch by the output limiter H_L.

$$\begin{cases} S_w = OFF & ; Q = 0 \ for \quad \mathrm{PID} \\ S_w = ON & ; Q \neq 0 \ for \quad \mathrm{P_{(ID)}} \end{cases}, \tag{3}$$

If the condition for $Q = 0$ or $|y-w| \leq H_L$, the compensator works as a PID controller due to the minor-loop is not activated. If the condition for $Q \neq 0$ or $|y - w| > H_L$, the integrator output imv is constrained by a minor-loop gain F. The derivative output is also constrained in the same rage. Hence, $\mathrm{P_{(ID)}}$ control has a constrained structure for an integrator and a derivative. F is defined by,

$$F = \text{Constant}, \quad \text{where} \quad 0 < F < 1. \tag{4}$$

The influence of the excessive control input is the smallest for $F = 1$ due to the integral output is full constrained. The general PID control works for $F = 0$. The features of proposed method, the integral action does not stop for $F \neq 1$.The heat shortage can be avoided for the tracking performance. The proposal method is an expanded application of a general bump transfer technique,which has the degree of freedom of $0 < F < 1$. When the system satisfies the sufficient condition which the process is the linear time-invariant system (LTI) and F is the constant value in the range of $0 < F < 1$, a stable transfer for the compensate input can be performed in a steady operating range. BIBO (bounded input bounded output stability) can be satisfied due to the controlled input is bounded and asymptotically stability can be satisfied in the same proof as the general bump transfer technique (Glattfelder and Schaufelberger (1983); Hanus et al. (1987)). In case of F is a variable parameter, it is necessary the more strict stability proof (Zhang and Evans (1988)).

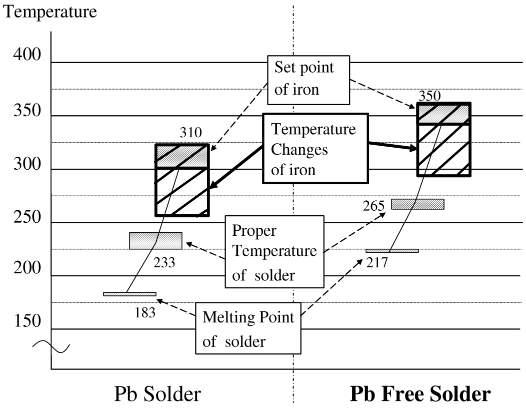

Fig. 4. Temperature change of Pb-free iron (left:Pb, right:Pb-free)

3.3 Basic concept of the derivative action

The iron temperature varies suddenly when the iron contacts with the printed circuit board or the solder. And also, when the iron separates from the printed circuit surface, the control performance is markedly reduced by the measurement noise. The derivative constraint is only activated in the range of $|y - w| > H_L$ to eliminate the influences. In the range of $|y-w| \leq H_L$,a general derivative term works without a limiter. The limiter for the derivative term is given by

$$dmv = \begin{cases} dmv & ; dmv < X \\ X & ; dmv \geq X \end{cases}, \tag{5}$$

where:

$$X = (pmv + imv - U_{max}) \times d_{lim}, \tag{6}$$

$$0 < d_{lim} < 1, \tag{7}$$

Using (5), the derivative kick is avoided by the coefficient d_{lim} so that the PID output $U = pmv + imv - dmv$ does not increase the maximum heater power U_{max}=100%. This approach is the same way of a software limiter for the derivative kick. Due to the input power for asymptotically stability is not influenced, the system can keep a stable condition (Glattfelder and Schaufelberger (1983); Hanus et al. (1987)).

3.4 The tuning of H_L

Fig.4 shows the temperature change of Pb-free iron. The left is Pb soldering. The right is Pb-free soldering. The appropriate Pb-free iron temperature for the melting point is in an extent of an oblique line. H_L is fixed as a constant parameter within the range $H_L \in [15, 50]$. H_L is tuned according to the types of iron. A user need not the tuning.

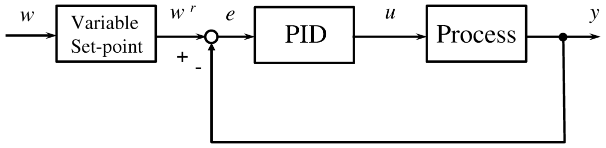

Fig. 5. Concept of Variable set point method (linear)

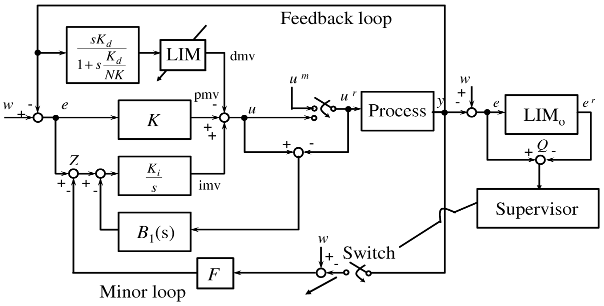

Fig. 6. Proposed method 2: Bumpless conditioned transfer type

3.5 *The initializing of compensator*

When the constraint of a compensator is large, namely, when a difference of $u \neq u^r$ is large by the discontinuous action of supervisor, a controlled output will jump. The quick convergence $u = u^r$ is required to remove a jump which causes an overheating. The general reset method for a state variable is applied. From (1), the output of a parallel type PID controller is only *imv* in the steady state. For this reason, *imv* as a state variable is memorized in the steady state and reset. After the soldering, the iron temperature decreases suddenly. The temperature output is determined between $i\%$ to $j\%$ of H_L as a following algorithm,

$$\text{IF}\quad H_L\frac{i}{100} \leq e \leq H_L\frac{j}{100} \quad \text{and} \quad \frac{\partial e}{\partial t} > 0 \quad \text{Then}$$
$$imv_{\_store} = imv. \tag{8}$$

4. THE VARIABLE SET POINT METHOD FOR A LOW MEMORY MPU

The basic proposed method in Section.3 cannot be applied to a low memory MPU. Since a lot of algorithms occupy the memory space of MPU. For a commercial controller, a more simple computer code is appropriate to minimize the controller cost. Peng et al. (1996) have presented a basic framework for the realizable reference or the variable set point method in Fig.5. In this paper, the variable set point method based on the output limiter in Section.3 is proposed for the Pb free soldering iron.

Firstly, Fig.3 can be redesigned to Fig.6. The bumpless transfer technique is introduced instead of the switching method of Fig.3 to remove a jump caused by the discontinuous action of superviser. Secondly, Fig.6 can be redesigned to Fig.7. An integrator *imv* is constrained by the minor loop $F_2\{e(s), s\}$ with the output limiter of (2). Finally, a variable set point w^r in Fig.8 is introduced instead of the setpoint w in Fig.7. Fig.7 can be transformed into Fig.5.

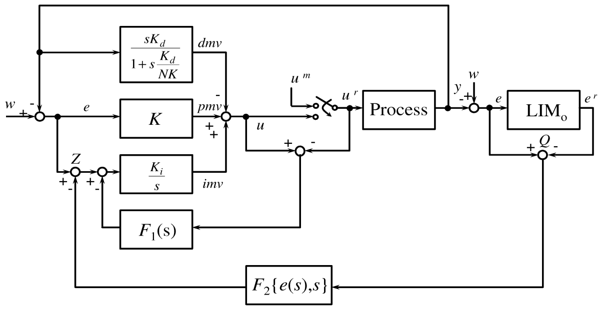

Fig. 7. Proposed method 3: Variable set point method (Nonlinear)

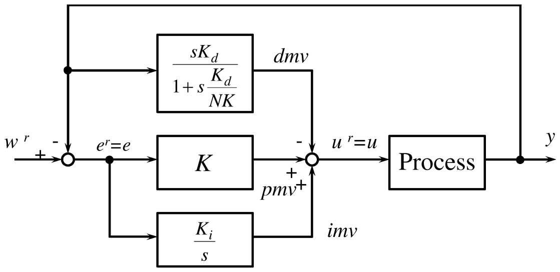

Fig. 8. Linear transformation of Fig.7

We considered that the compensator output u and error e in Fig.8 are equal to the real process input u^r and the limiter output e^r in Fig.7, respectively. Namely, the nonlinear elements of the bumpless transfer and the output limiter are not activated under the conditions $u^r = u$ and $e^r = e$. When w^r is introduced in Fig.7, we assume that u^r,e^r and y described in Fig.8 are equivalent to u^r,e^r and y described in Fig.7, respectively. The control structure does not include nonliniarity which is hidden in the variable set point w^r.

From Fig.8, the process input u^r is given by

$$u^r = \left(K + \frac{K_i}{s}\right) w^r - \left(K + \frac{K_i}{s} + \frac{sK_d}{1 + sK_d/(KN)}\right) y, \tag{9}$$

this yields

$$w^r = \frac{s^2 \frac{K_d}{K_i}\left(1 + \frac{1}{N}\right) + s\frac{1}{K_i}\left(K + \frac{K_d K_i}{KN}\right) + 1}{\left(1 + s\frac{K}{K_i}\right)\left(1 + s\frac{K_d}{NK}\right)} y + \frac{s\frac{1}{K_i}}{s\frac{K}{K_i} + 1} u^r. \tag{10}$$

When the bumpless transfer and the output limiter are activated, $u^r (= u)$ or $e^r (= e)$ keeps constant value in spite of $F_i (i = 1, 2)$ if the initial conditions of the integrator are the same. On the other hand, when the constraints are not activated, $F_1 = 1/K_a$、 $F_2 = 1/K_b$ are defined to converge $u^r = u$, $e^r = e$ for the linearization. From Fig.7, the compensator output u is given by

$$u = \left(K + \frac{K_i}{s}\right) w - \left(K + \frac{K_i}{s} + \frac{sK_d}{1 + sK_d/KN}\right) y$$

$$+\frac{K_i}{s}\left(\frac{u^r-u}{K_a}\right)+\frac{K_i}{s}\left(\frac{e^r-e}{K_b}\right). \quad (11)$$

Subtracting (11) from (9), the variable setpoint w^r is given by

$$\begin{aligned} w^r &= w+\frac{1+s\frac{K_a}{K_i}}{K_a(1+s\frac{K}{K_i})}(u^r-u) \\ &\quad +\frac{1}{K_b(1+s\frac{K}{K_i})}(e^r-e) \\ &= w+G_{w1}(s)(u^r-u)+G_{w2}(s)(e^r-e). \quad (12) \end{aligned}$$

G_{w1} with respect to u^r is reduced to a static gain from a dynamic transfer function with a pole and a zero. w^r can converge to w quickly when the constrains ($u^r = u$、$e^r = e$) are achived. During $u^r \neq u$, y tracks w^r due to w^r is different from w. After convergence $u^r = u$, the controller achives $w^r = w$ so that y tracks w which has the same dynamics of closed loop step response. This is the same as the bumpless transfer by

$$G_{w1}(s) = 1/K, \quad (13)$$

where, $K_a = K$. G_{w2} which inherits the concept of Section.3 is given as a dynamic filter with K_b,

$$K_b \;=\; \begin{cases} \dfrac{H_L-e}{e\cdot F} & ;e>0 \\ \dfrac{H_L+e}{e\cdot F} & ;e<0 \end{cases} \quad (14)$$
$$\text{where} \quad 0<F<1.$$

A smooth converge is achieved by a dynamic filter to avoid the influence of a discrete operation (14). The variable setpoint w^r is given by

$$w^r = w+\frac{1}{K_b(1+sT_i)}(e^r-e)+\frac{u^r-u}{K}, \quad (15)$$

where $T_i = K/K_i$.

The system stability can be proved based on asymptotically stable (Glattfelder and Schaufelberger (1983); Hanus et al. (1987)). The proposed method wrote w to replace w^r so that u^r is equal to u and e^r is equal to e. In (11), u^r and e^r will be approaching the constant values and u will cleally asymptotically converge when the nonliner elements are activated. When the nonlinear elements are not activated, u^r and e^r will be approaching $u^r = u, e^r = e$ and u will clealy asymptotically converge by the third and forth term of (11) are zero. Furthermore, in (9) and (10), the same asymptotically stable can be proved by the converge of w^r and u^r. The derivative term is introduced as the same alglorism of (5). Due to the third term of (15) with respect to bumpless transfer will be approaching $u^r = u$, the derivative action can also achive asymptotically stable.

4.1 The features of proposed method

The features is that the proposed method leave a closed loop of PID as it is without changing. And the variable setpoint w^r can be tuned by the proportional gain K and the integration coefficient K_i of PID parameters. The dynamic filter of (15) has the adequate convergence speed due to PID is tuned as the astatic process. Hence, the proposed method can reduce the program code and also be easily applied in practice.

5. EXPERIMENTS

The proposed methods were applied and tested to a commercial controller for a Pb-free soldering iron based on TTM-000 series (Toho electronics Inc.). The PID parameter was tuned by an auto tuning function (Hamane et al. (2005)) under the same condition for the end user. An actual soldering was performed under the same condition at all the examinations. The temperature set point is 350 ℃. F and H_L are fixed to 0.7 and 25 ℃, respectively.

In the experimental results, the oscillation at the steady state is a result of every soldering for three seconds. The temperature oscillates when the iron contacts with the printed circuit board. When the classical PID controller is used in Fig.9, the average of the oscillation amplitude raises as the frequency of soldering increases. The oscillation is not removed due to the thermal capacity of the iron is small. And a large overshoot occurs after the last soldering. The range of load variation is shown in Fig.13. The proposed method 1,2 and 3 shown in Fig.10, Fig.11 and Fig.12. The proposed methods could solved the oscillation problem. The average of the amplitude is stabilized and the overshoot is small. This improvement in case of the proposed method 3 is shown in Fig.13. The proposed methods were satisfied the temperature change of Pb-free iron in Fig.4. And also a quality criterion of the Pb-free soldering was satisfied. These proposed methods can extend the life-time of the Pb-free iron and the thermal breakdown can be avoided by the removing the overheating. The proposed method 3 based on the variable set point method is particularly good memory consumption of MPU from the proposed methods.

6. CONCLUSION

The proposed PID control strategy has been successfully applied to the Pb-free soldering iron temperature controller. This controller has been commercialized. A wide variety of applications are possible, e.g. the packaging machine which has the same characteristic as the soldering iron.

ACKNOWLEDGEMENTS

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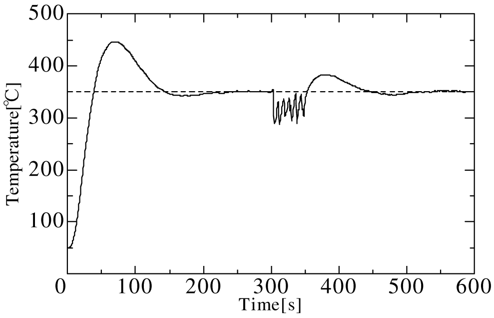

Fig. 9. The problem of PID control

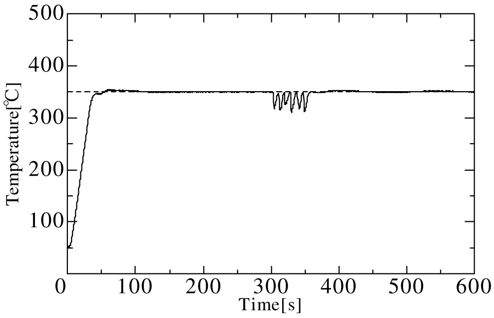

Fig. 10. Proposed1: Conditioned transfer type method

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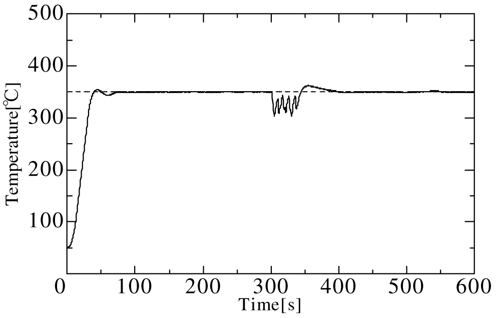

Fig. 11. Proposed2: Bumpless conditioned transfer type method

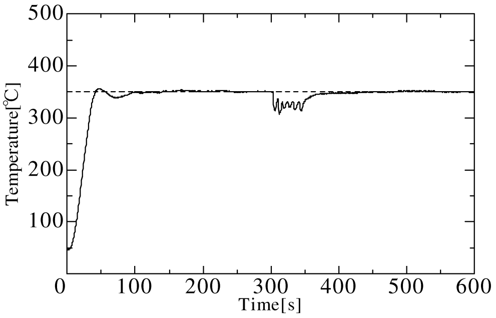

Fig. 12. Proposed3: Variable set-point method

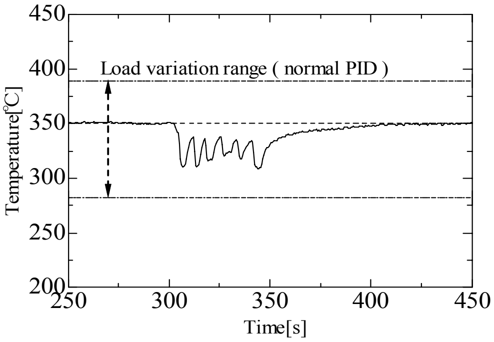

Fig. 13. The magnification of Fig.12