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SENSORLESS CONTROL METHOD OF INSTANT-HEATING MODULE FOR A BIDET

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ABSTRACT

In this paper, we propose the sensor-less control method for instant-heating module for a bidet, which can control water temperature effectively without using the flow-velocity sensor of the flowing water. By monitoring the changes in outlet water temperature and analyzing them with the information of inlet water temperature and the switching command for Triac, we can estimate the value of the velocity of the flowing water. This information can be effectively acquired during cleaning operation of bidet system. Therefore, we can expect that the proposed method can be easily integrated with the previous low-cost control schemes. To illustrate the validity of the proposed method, experimental works are done under various operating conditions.

KEY WORDS

Power Electronics Application, Instant-Heating Module, Sensor-less Control, Bidet

1. Introduction

With the elevation of the standard of living, a bidet becomes a necessity in the modern home. There are three types of temperature control schemes for a bidet system.

Type 1) Mechanical Type: Both hot water and cold water are supplied to bidet system and users can control outlet water temperature by adjusting mechanical valve.

Type 2) Hot Water-Tank Type: Temperature in outlet water is slowly controlled in the hot water tanks and this condition is maintained even when bidet system is not used.

Type 3) Instant-Heating Module Type: Temperature in outlet water is controlled directly by using ceramic heater and switching devices only when users use bidet system.

Type 1 can be most cost-effective, but it cannot be applied unless both hot water and cold water are supplied. Type 2 is used at first with its moderate material cost. However, unnecessary energy for maintaining hot water temperature is consumed while bidet is not in operation and there may exist sanitary problem such as micro-organism in hot water-tank. Type 3 can resolve such problems but additional cost for instant-heating module and control circuits can be a problem in cost-sensitive consumer markets. With the trend of low energy consumption, the portion of Type 3 control scheme in the market is increasing.

Since control commands for instant-heating module can be generated from inlet water temperature, outlet water temperature (command), and the velocity of flowing water, a velocity sensor for flowing water is attached in the instant-heating module. This can result in cost increase and reliability problems. Therefore, it needs to develop sensor-less control schemes for instant-heating module to lessen cost-increase and to achieve more reliable system. It should be noted that to avoid any increase in material cost, all algorithm should be implemented in software [1].

This paper is consisted as follows. First, we derive a steady state model and simplified model of instant-heating module and describe its control problem briefly. Then, we propose an estimation algorithm for the value of flow-velocity of water. Experimental works are depicted to show the validity of the proposed sensor-less control schemes and concluding remark follows.

2. Modelling of Instant-Heating Module

To derive steady-state model of instant-heating module, we ignore temperature change in heater itself. Then, heater can be modelled as an element with constant resistance R and total energy ΔQ_{total} generated during time interval of Δt can be divided by the energy ΔQ_{water} transferred to the water and the energy $\Delta Q_{heater-air}$ dissipated to the air.

$$\frac{(V^*_{\mathrm{rms}})^2}{\mathrm{R}}\Delta t = \Delta \mathrm{Q}_{\mathrm{total}} = \Delta \mathrm{Q}_{\mathrm{water}} + \Delta \mathrm{Q}_{\text{heater-air}}, \qquad (1)$$

where V^*_{rms} represents root-mean-square voltage command.

Meanwhile, the energy $\Delta Q_{\mathrm{water}}$ transferred to the water at steady-state can be written as follows[2].

$$\Delta \mathrm{Q}_{\mathrm{water}} = \rho \upsilon \mathrm{A}_{\mathrm{c}} \mathrm{C}_{\mathrm{p}} (\mathrm{T}_{\mathrm{out}} - \mathrm{T}_{\mathrm{in}}) \Delta \mathrm{t}. \qquad (2)$$

Here, ρ means density of water and υ means flow-velocity of water. A_c represents cross sectional area of the pipe and C_p represents specific heat of water at constant pressure. T_{out} and T_{in} represents outlet water temperature and inlet water temperature, respectively.

The control problem of instant-heating module can be stated a problem that for a given ρ, υ, A_c, C_p, T_{in}, and T_{out}, find V^*_{rms} to get desired outlet water temperature $T_{out,desired}$. To derive control law for instant-heating module, we make additional assumptions as follow.

(A.1) The flow-velocity of water changes very slowly.

(A.2) Total energy ΔQ_{total} generated by heater is used mainly for heating water. That is,

$$\Delta Q_{\mathrm{total}} \approx \Delta Q_{\mathrm{water}} \qquad (3)$$

Under these assumptions, we can restate control problem of instant-heating module at steady-state as finding V^*_{rms} as follows.

$$V^*_{rms} = \sqrt{R\rho\upsilon \mathrm{A}_{\mathrm{c}} \mathrm{C}_{\mathrm{p}} (\mathrm{T}_{\mathrm{out}} - \mathrm{T}_{\mathrm{in}})} \qquad (4)$$

Equation (4) can be rewritten as follows

$$\mathrm{T}_{\mathrm{out}} = \mathrm{T}_{\mathrm{in}} + \frac{(V^*_{rms})^2}{R\rho\upsilon \mathrm{A}_{\mathrm{c}} \mathrm{C}_{\mathrm{p}}} \qquad (4)'$$

In practical bidet system, control law of switching command of (4) is used with additional compensation laws to get faster response time and to compensate un-modelled dynamics including parameter uncertainties.

Since equation (4) is satisfied only at steady-state with the assumptions (A.1) to (A.2), we cannot use equation (4) directly for control and estimation. So, instead of using equation (4) directly for control, we use simplified cascade time-delay model as in Fig. 1

In Fig.1, dashed box represents instant-heating module. The first block in the dashed box represents characteristics of instant-heating module at steady-state. $1/(1+\tau_2 s)$ of the second block represents characteristics of instant-heating module for reaching steady-state as low pass filter of order 1 and $(1-e^{-\tau_1 s})/s$ of the second block represents the time required for inlet water to pass through the pipe of instant-heating module. Since the value of time delay and low pass filter coefficient is inversely proportional to the flow-velocity of water, we present it in the above block diagram.

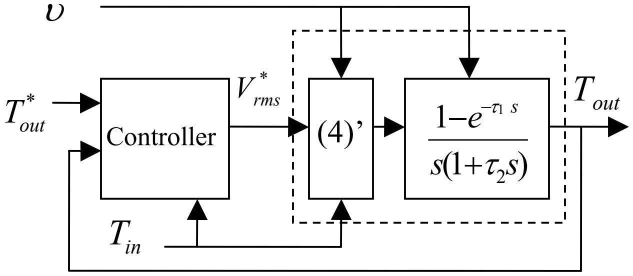


Fig. 1 Simplified cascade time-delay model

3. Estimation Algorithm for Flow-Velocity

For bidet system, cleaning operation for a tip is executed at first stage. During this operation, temperature control accuracy is not critical and we can make estimation of flow-velocity at this stage.

Since instant-heating module has large time-delay, it takes long time to reach steady-state. Moreover, switching noise of Triac[3] makes sensing temperature data T_{out} hard to handle. Therefore, the effect of variations in voltage (switching) command on changes in outlet water temperature cannot be observed easily.

However, by observing filtered data of outlet temperature to remove switching noise and using maximum difference data of filtered value, we can estimate the flow-velocity of water effectively. Fig.2 shows the flowchart of estimation algorithm during cleaning operation.

Note that voltage (switching) command V^*_{rms} is determined experimentally to satisfy the following requirements.

(R.1) By observing filtered value of T_{out}, we can check error condition such as flow-velocity of water being zero.(no inlet water case)

(R.2) Time-difference $\Delta T_{out,filtered}$ should reach its maximum value within a certain time for all allowable value of flow-velocity of water.

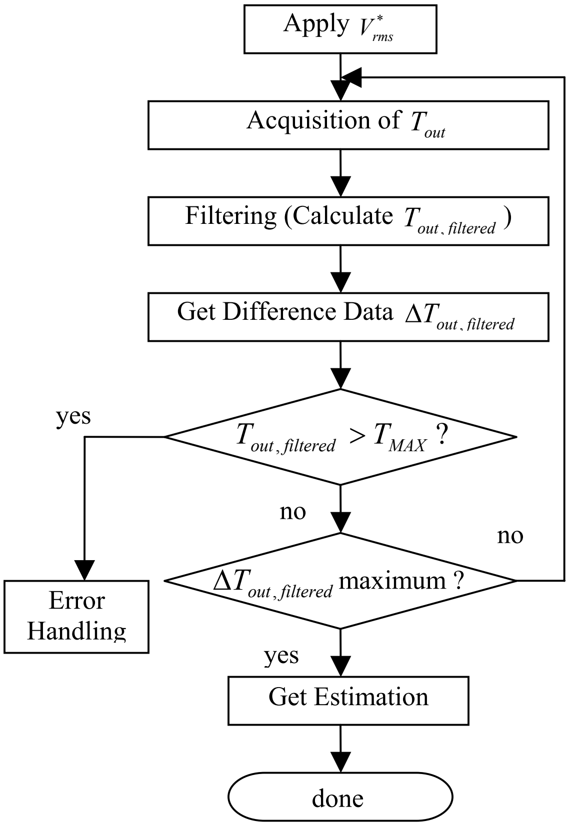


Fig. 2 Estimation algorithm during cleaning operation

4. Experimental Results

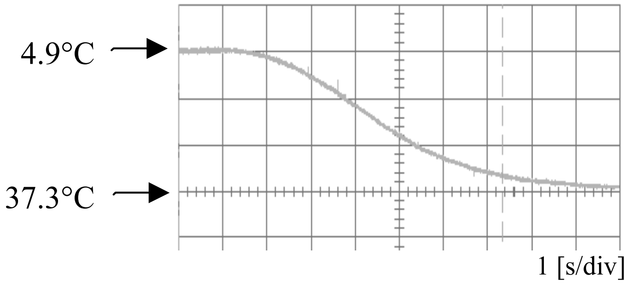
The specification of instant-heating module for our experiment is as follows.

Resistance of ceramic heater	22.3Ω
Volume of the pipe of heater	18 cc
Allowable flow-velocity of water	300~720 cc/min
Rated power	1300 W

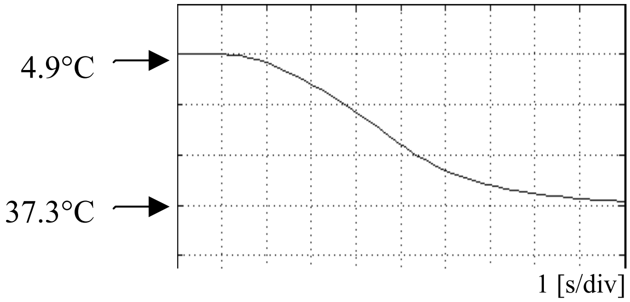
To see the validity of proposed simplified model, step response of instant-heating module is depicted in Fig. 3.

Here, we use $\tau_1 = 3s$ and $\tau_2 = 2.6s$ and we can observe that simplified model matches well with true system.

Note also that, instead of plotting the value of outlet water temperature, we plotted voltage divided by thermister. The relationship between divided voltage and water temperature is approximated through experiments as in Fig. 4. Here, clipped area is used for checking error conditions.



(a) Step response of true system



(b) Step response of simplified model

Fig. 3 Step response (V^*_{rms} =0.5 V^*_{rms} , υA_c =360cc/min)

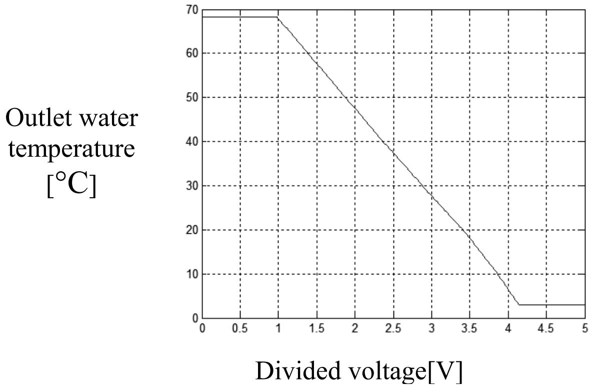
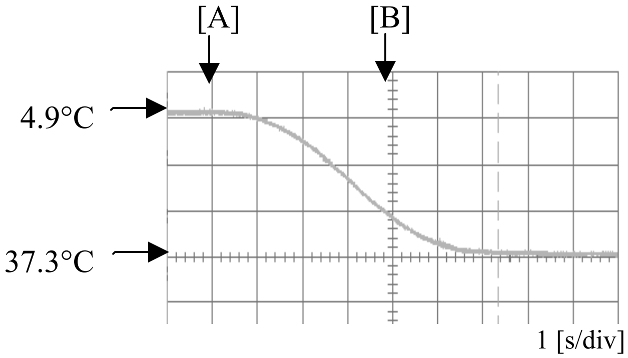


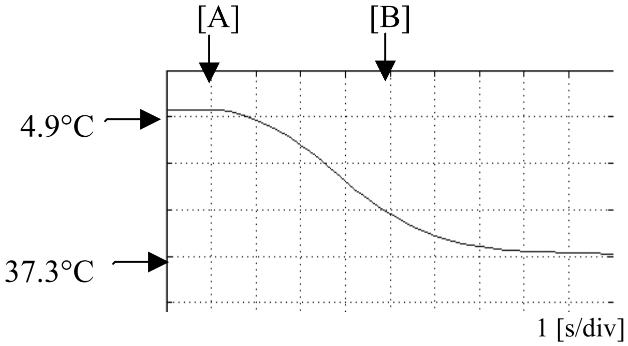
Fig. 4 Relationship between divided voltage and outlet water temperature

To achieve faster response time, we can use somewhat larger value of voltage command than equation (4) at first. This condition is depicted in Fig. 5 where at time [A] voltage command $V^*_{rms} = 0.6V_{rms}$ is applied and at time [B], voltage command $V^*_{rms} = 0.5V_{rms}$ is applied

Comparing with Fig. 3, we can see faster response time can be achieved. Moreover, we can expect that the shortest response time can be achieved by applying maximum voltage at first. However, due to the large time-delay in instant-heating module, it can cause considerable overshoot. So, the condition for changing voltage command and the value of initial voltage(switching) command should be deliberately checked and tuned intensively.

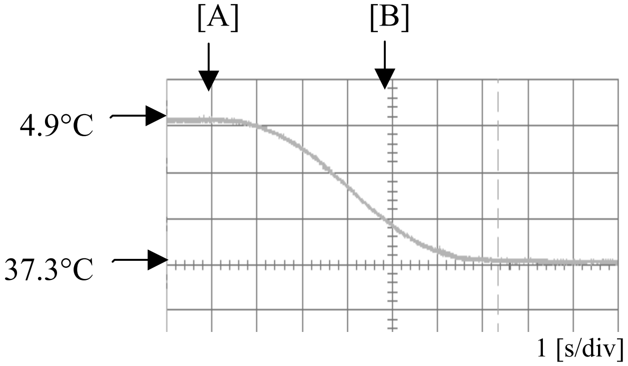


(a) Modified step response of true system

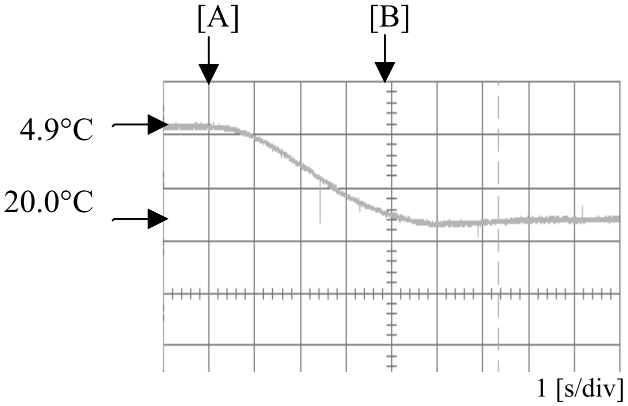


(b) Modified step response of simplified model

Fig. 5 Modified command for faster response (V^*_{rms}=0.6 V^*_{rms} →0.5 V^*_{rms} ,, υA_c =360cc/min)



(a) Modified step response for υA_c =360cc/min



(b) Modified step response for υA_c =675cc/min

Fig. 6 Modified step response for different flow-velocity

To show the validity of the proposed estimation scheme, we applied modified step command for different flow-velocity conditions, as is depicted in Fig. 6. Here, we can observe that by using maximum time-difference $\Delta T_{out,filtered}$ of the filtered value of outlet water temperature, flow-velocity can be easily estimated.

5. Conclusion

In this paper, we propose the sensor-less control method for instant-heating module for a bidet, which results in cost effectiveness and reliability. By monitoring the changes in outlet water temperature and analyzing them with the information of inlet water temperature and the switching command for Triac, we can estimate the value of the velocity of the flowing water. This information can be effectively acquired during cleaning operation of bidet system. Therefore, we can expect that the proposed method can be easily integrated with the previous low-cost control schemes. To illustrate the validity of the proposed method, experimental works are done under various operating conditions. Remaining works are related to resolving problems in mass production such as developing reliable automatic tuning algorithm to apply the proposed scheme for commercial use.

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