Rotational Angle Trajectory Tracking of a Twisted Polymeric Fiber Actuator by the Combination of a Model-Based Feed-Forward and Estimated Temperature Feedback

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***Abstract*—In this letter, an angular trajectory tracking controller for a twisted polymeric fiber (TPF) actuator by the combination of a model-based feed-forward and estimated temperature feedback is proposed. TPF actuator is one of the soft actuators that can produce a rotational motion, which is made by twisting a nylon yarn and thermally treating it. Adding a feed-forward controller with a feedback controller makes it possible to reduce a phase lag and realizes a higher frequency response compared with using only the feedback controller when performing a time-dependent trajectory tracking. First, temperature–angle, resistance–temperature, and voltage–temperature models are composed, respectively, and then combined in order to design a feedforward controller. Next, parameter estimation is performed through experiments using the prototype of a rotational actuation module. Finally, trajectory-tracking experiments are conducted using a prototype to demonstrate that the proposed method can improve the tracking performance by reducing the phase lag.**

***Index Terms*—Soft Material Robotics, Flexible Robots, Motion Control.**

I. Introduction

A Twisted Polymeric Fiber artificial muscle actuator, which is proposed by Haines *et al.* [1], has attracted much attention as a quiet, lightweight, and inexpensive actuator. It is made by twisting a nylon thread such as a fishing line and performing heat treatment to fix its shape. Although there have been many names of these actuators and in this letter, it is called TPF actuator hereinafter [2]. The TPF actuator can be classified into two types. One is called Twisted and Coiled Polymeric Fiber (TCPF) actuator which produces a contraction motion. The other is called just a TPF actuator which produces a rotational motion. The rotational type TPF actuator has not received much attention even though many studies related to the contraction type TCPF actuator has been reported, so far (e.g. [3]–[8], etc.). Takagi *et al.* evaluated the response characteristics according to the temperature, and proposed a black-box model for the rotational TPF actuator and a torque feedback controller using the proposed model [9]. This method makes a good performance to realize the desired torque by using a simple feedback controller. Jafarzadeh *et al.* implemented the Takagi-Sugeno-Kang (TSK) controller as a fuzzy controller to improve the response with avoiding the saturation of the input voltage and overshoot [10]. However, a torque sensor is required to compose a feedback controller in both studies.

Not only to control the output torque but also to regulate the rotational angle is equally important in order to use it as one of the substituting candidates of a conventional rotational motor. Suzuki *et al.* proposed an antagonistically driven mechanism using a pair of TCPF actuators to improve its response using the combination of feedback and feed-forward controllers[11]. The response in the elongation state can be improved by the antagonistic actuation and thus the tracking error can also be reduced. It makes a good performance although it requires a laser displacement sensor to measure the length of the actuator in real-time. Generally, a rotational angle sensor such as an encoder or potentiometer is necessary in order to consist of a feedback controller when regulating a rotational angle of an actuator. However, these sensors cost and are heavy compared with the TPF actuator, and such mechanical sensors may induce disturbance forces such as friction or inertial force to the actuator. Therefore, to use these sensors is not suitable for the actuator because the advantage of the actuator such as lightweight or low cost should vanish and several sensor-less control methods have been proposed so far.

Masuya *et al.* proposed a sensorless feed-forward position controller using the TCPF actuator based on a nonlinear model [12]. It is effective, however, it sometimes makes a steady state error due to the difference between the determined model and

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a real situation because of no feedback. In addition, Masuya's model is quite complicated and many parameters have to be determined beforehand. Suzuki *et al.* proposed a length displacement observer based on Kalman filter from the change in resistance of heating wire used as a heater to add Joule heat to the TCPF actuator, and a length feedback controller is proposed using the estimated length[13]. This method can estimate the length of the TCPF actuator from the change in resistance of metal wire wound as a heater in real-time. However, the estimation accuracy becomes degraded when a load change is relatively high because the change in resistance due to the temperature is much dominant compared with that due to the change in length. Van der Weijde *et al.* proposed a self-detection method to estimate a deflection, force, and temperature of an actuator by measuring the electrical impedance of a heating wire [14]. Although this method can estimate multiple state variables simultaneously. However, the static situation is assumed and it is necessary to have an LCR meter or impedance analyzer which generally costs and are not compact. Schimmack *et al.* proposed an extended Kalman filter as an observer to estimate the current, temperature, displacement, contraction speed of the TCPF actuator, and proposed an adaptive controller for tracking a time-dependent trajectory [15]. However, its real-time computing cost is relatively high as the authors mentioned in the paper. It means that the low cost, which is one of the advantages of the actuator, should sacrifice.

We also proposed an estimated temperature feedback control method for the rotational type TPF actuator [2]. It utilizes two types models of the actuator, one is a temperature-to-angle model, and the other is a change in the resistance-to-temperature model. It makes a sufficient performance when the desired angle is given as a time-independent constant value. However, when the desired angle is given as a time-dependent smooth trajectory, it becomes difficult to track the desired trajectory in the desired performance by only using a feedback controller. It is because the input of the TPF actuator is thermal energy and thereby it intrinsically owns relatively a large time constant compared with the commonly used electrical actuator. In such a system with a large time constant, a phase lag of the response generally becomes considerable. In order to cope with the considerable phase lag which is a drawback of the only feedback controller, we propose a new controller that combines the estimated temperature feedback control as we proposed in the previous work [2] with a model-based temperature feed-forward control to regulate the angle of the actuator.

The input to the TPF is heat, and heating the TPF actuator by Jule heating using some electro conductor is one of the common methods. However, the TPF actuator is made of nylon thread and therefore it cannot be electrically heated directly. Foroughi *et al.* [16] proposed a torsional carbon nanotube artificial muscle as one of the soft rotational actuators. The carbon nanotube itself can be regarded as an electric conductor and thus it is easy to add heat by Jule heating. However, it costs due to the carbon nanotube, and it can be actuated only in an electrolyte. Another method to add Jule heat is to use a silver-plated nylon thread [5]. However, the types of silver plated nylon are very limited and especially there are few types of thick radius nylon thread. The output torque of the rotational-type TPF actuator is proportional to the radius of the actuator and thus the output torque is limited when using the silver plated nylon thread. Kim *et al.* [17] used a pure nylon thread as an actuator and a silver-plated nylon thread as a conductor for a contraction-type TPF actuator. It can produce a large force and displacement compared with the other contraction-type TCPF actuator. However, it is difficult to adapt Kim's method to the rotational-type actuator because its motion is not a contraction motion but a rotational motion.

In this study, a relatively thick pure nylon thread is used as a TPF actuator, and an enameled wire is directly wound as a heater. The reason why we chose an enameled copper wire as a heater is that it is able to avoid an electrical short circuit because covered by enamel and easy to wind due to softness. Moreover, it has a large change in resistance with a temperature, whose nature is important to accurately estimate the actuator's temperature in this study.

In what follows, firstly two-types models of the TPF actuator are formulated. One is from the desired angle to the desired change in temperature model, and the other is from the present change in resistance to the present change in the temperature model. By using these two models, the feedback controller and feed-forward controllers are composed each and combine them eventually. Next, each parameter these models contain is estimated through the experimental identification. Finally, in order to confirm the effectiveness of the proposed method, tracking experiments are carried out and its usefulness is verified.

II. Modeling of the TPF Actuator and Its Control Design

A block diagram of the proposed control method is shown in Fig. 1. As shown in the figure, firstly the desired change in temperature is obtained from the given desired angle using the inverse model of the change in temperature to the angle. In the feedback control part, the present change in temperature value is estimated through the model of the change in resistance to the change in temperature, and the temperature feedback controller is composed using the difference between the estimated change in temperature to the desired change in temperature. In the feed-forward control part, the desired input voltage is obtained from the inverse model of the input voltage to the change in temperature. The final control input voltage to regulate the rotational angle of the actuator is composed by the summation of both the obtained feedback and feedback control inputs.

Here, it is assumed that the temperature of the actuator is spatially uniform and there is no spatial temperature gradient. It is because the length of the actuator used in this study is relatively short (25 [mm]), the enameled wire as a heater can be regarded as to wind densely enough with an equal interval as shown in Fig. 2, and the ambient temperature is kept constant by the thermostatic chamber. The detail of the experimental setup will be described in Section III.

A. *Inverse Model of the Change in Temperature to the Angle*

Yip *et al.* proposed the temperature to the contraction displacement model of the TCPF actuator [5]. We also derive the

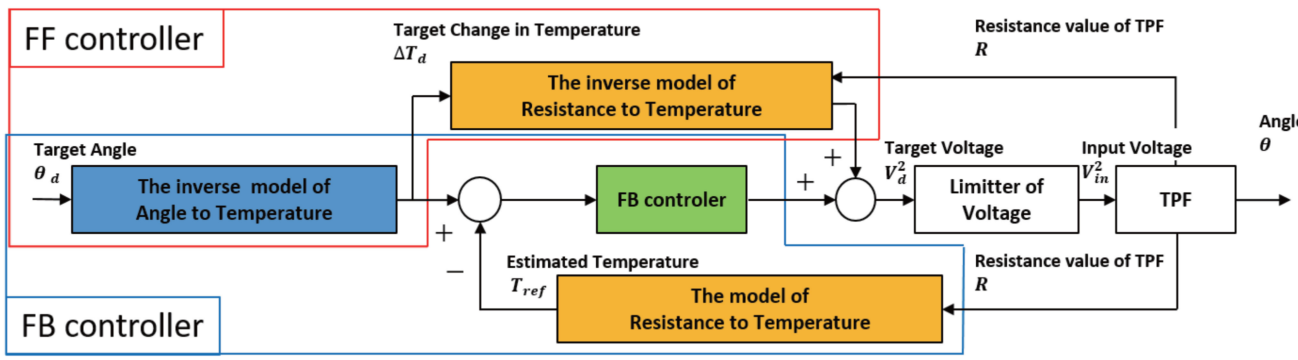

Fig. 1. Block diagram of the proposed rotational angle controller.

Fig. 2. Microscopic photo of the TPF actuator.

temperature to the rotational angle model of the rotational-type TPF actuator based on the Yip's model. When the Yip's model is used as the model of the contraction-type TCPF actuator, a certain initial tension is necessary for the actuator. The initial tensile force direction and the actuation direction are the same and thus it is necessary to consider the initial tension as a load force. On the other hand, the rotational-type TPF actuator makes a rotational torque whose direction is orthogonal to the initial tensile force. Additionally, in our model, there is the only rotational joint that is very light and can rotate very smoothly and no other disturbance load. Therefore, we eventually assumed the disturbance torque $\tau = 0$ and thus the temperature to the rotational angle model is given as follows:

$$c\Delta T = b\dot{\theta} + k_s\theta \tag{1}$$

where θ denotes the rotational angle of the TPF actuator from its origin, ΔT denotes the change in temperature value from the initial temperature of the TPF actuator, c denotes a constant that correlates the change in temperature value and the generated torque of the TPF actuator, which Yip *et al.* called it the temperature coefficient [5]. Additionally, b denotes the viscosity coefficient and k_s denotes the spring constant when the TPF actuator is regarded as a passive torsional spring, assuming that it can be determined independently from its temperature. By taking the Laplace transform of Eq. (1), we obtain

$$\theta = \left(\frac{c/b}{\mathrm{s} + k_s/b}\right)\Delta T = G_{T\theta}(\mathrm{s})\Delta T. \tag{2}$$

In our proposed controller, the inverse model of Eq. (2) is required because the desired change in temperature according to the given desired angle is needed to compose both the feedback and feed-forward controllers. In general, the inverse model of the transfer function becomes not proper and thereby it is impossible to implement to the controller as it is. In order to implement the inverse model of the change in temperature to the displacement, Yip *et al.* and Masuya *et al.* utilizes a low-pass filter with the inverse model of the change in temperature to the displacement in their feed-forward controllers for the TCPF actuator. In accordance with their works, we also introduce a low-pass filter in this study in the following way such that:

$$\Delta T = \frac{1}{1+\tau\mathrm{s}}G_{T\theta}^{-1}(\mathrm{s})\theta \tag{3}$$

where τ denotes the arbitrarily given parameter to determine the time constant of the low-pass filter. By using Eq. (3) as an inverse model of the change in temperature to the angle, the desired change in temperature value is obtained from the desired angle. By discretizing the Eq. (3), we obtain:

$$\Delta T_k = a_1\Delta T_{k-1} + a_2\theta_k - a_3\theta_{k-1} \tag{4}$$

where

$$a_1 = \tfrac{\tau}{\tau+\Delta t},\ a_2 = \tfrac{b+k_s\Delta t}{c(\tau+\Delta t)},\ a_3 = \tfrac{b}{c(\tau+\Delta t)}$$

These are constant parameters which are determined through identification experiments before implementation.

B. Change in Resistance to the Change in Temperature Model

Tahara *et al.* proposed a partially nonlinear model of the change in resistance to the change in temperature [2], which is based on the Yip's linear model for the TCPF actuator. In this study, we utilize the Tahara's model which is given as follows:

$$C_v\Delta\dot{T} = P(V^2, R) - \alpha S_c\Delta T \tag{5}$$

$$P(V^2,R) \simeq \frac{\partial f}{\partial R}\Delta R + \frac{\partial f}{\partial V^2}\Delta V^2 + \frac{\partial^2 f}{\partial R^2}\Delta R^2 + \frac{\partial^2 f}{\partial R\partial V^2}\Delta R\Delta V^2, \tag{6}$$

where C_v denotes a heat capacity, V denotes an input voltage, R denotes a resistance value of the heating wire generating Joule heat which depends on the temperature, α denotes a convective heat transfer coefficient, and S_c denotes the surface area of the TPF actuator exposed to convection. Also, $\Delta V^2 = V^2 - V_o^2$ and $\Delta R = R - R_o$. By substituting Eq. (6) into Eq. (5) and discretizing it with a sampling time Δt, we obtain:

$$C_v \frac{\Delta T_k - \Delta T_{k-1}}{\Delta t} = -\alpha S_c \Delta T + \frac{\partial f}{\partial R}\Delta R + \frac{\partial f}{\partial V^2}\Delta V^2 + \frac{\partial^2 f}{\partial R^2}\Delta R^2 + \frac{\partial^2 f}{\partial R \partial V^2}\Delta R \Delta V^2$$

$$\therefore \Delta T_k = b_1 \Delta T_{k-1} + b_2 \Delta R_k + b_3 \Delta V_k^2 + b_4 \Delta R_k^2 + b_5 \Delta R_k \Delta V_k^2, \quad (7)$$

where

$$\begin{bmatrix} b_1 = \frac{C_v}{C_v + \alpha S_c \Delta t}, & b_2 = \frac{\Delta t}{C_v + \alpha S_c \Delta t}\frac{\partial f}{\partial R} \\ b_3 = \frac{\Delta t}{C_v + \alpha S_c \Delta t}\frac{\partial f}{\partial V^2}, & b_4 = \frac{\Delta t}{C_v + \alpha S_c \Delta t}\frac{\partial^2 f}{\partial R^2} \\ b_5 = \frac{\Delta t}{C_v + \alpha S_c \Delta t}\frac{\partial^2 f}{\partial R \partial V^2} & \end{bmatrix}$$

These are also constant parameters which are determined through identification experiments before implementation. The estimated temperature feedback controller employs the change in temperature ΔT_k obtained by Eq. (7) as the present change in temperature.

C. Inverse Model of the Input Voltage to the Change in Temperature

In the feed-forward controller, the desired input voltage is obtained from the desired change in temperature through the inverse model of the input voltage to the change in temperature. In Eq. (6), the change in resistance is chosen as an input and the change in temperature is chosen as an output. On the other hand, Eq. (7) can also be taken as the model that the voltage is as an input, and the change in temperature is as an output. In order to compose the feed-forward controller, the inverse model from the voltage as an input to the change in temperature as an output is required which can be given as follows:

$$\Delta V_k^2 = \frac{\Delta T_k - b_1 \Delta T_{k-1} - \Delta R_k (b_2 + b_4 \Delta R_k)}{b_3 + b_5 \Delta R_k} \quad (8)$$

where the parameters $b_1 \sim b_5$ should be the same as the parameters expressed in Eqs. (7) and (8). Therefore, each parameter is estimated using the forward model as Eq. (7), and the same estimated parameters are used in Eq. (8). When implementing Eq. (8), the desired change in temperature value ΔT_{d}, which is derived using the inverse model of Eq. (4), is used as ΔT_k, and the measured resistance value is used as the present resistance value R_k. The current change in resistance value is used not only in the feedback controller but also to update the feed-forward model. This makes it possible for the controller to be robust for the change in temperature of the environment. In theory, it is necessary to make the inverse model of Eq. (8) to be proper. However, in this letter, the backward-difference approximation model is used for the inverse model of the input voltage to the change in temperature, and any low-pass filter is not utilized. It is because the model of the input voltage to the temperature change is not of linear in our model, and its response can be assumed to be slow.

D. Proposed Controller Combining a Model-Based Feed-Forward and an Estimated Temperature Feedback

We compose a new controller combining a model-based feed-forward and estimated temperature feedback. It is known that there is a limitation in improving the performance to track a time-dependent trajectory due to a time delay when only using a feedback controller. In order to cope with this, a model-based feed-forward controller is newly introduced in this letter. This is also advantageous that an overheating induced by the feed-forward or feedback controller can be prevented because the current temperature of the TPF actuator is always estimated using the model, and thus it is possible to increase the feedback gains. First, after setting the desired angle, the desired change in temperature ΔT_{d} is obtained from the inverse model of the temperature to the angle and the estimated change in temperature ΔT_{ref} is obtained from the resistance value to the temperature model. By using them, an estimated temperature feedback input u_{FB} is given as follows:

$$u_{\mathrm{FB}} = K_p e(t) + K_i \int_0^t e(t) \mathrm{d}t \quad (9)$$

$$e(t) = \Delta T_{\mathrm{d}} - \Delta T_{\mathrm{ref}} \quad (10)$$

Also, the feed-forward input u_{FF} is constructed as follows using the input voltage to the temperature model using Eq. (8).

$$u_{\mathrm{FF}} = \left\{ \frac{R_{\mathrm{TPF}} + R_2}{R_2} \right\}^2 \frac{\Delta T_k - b_1 \Delta T_{k-1} - \Delta R_k (b_2 + b_4 \Delta R_k)}{b_3 + b_5 \Delta R_k} \quad (11)$$

The final input V_{d}^2 is constructed as a linear combination of u_{FF} as shown in Eq. (10) and u_{FB} as shown in Eq. (11). It is given as follows:

$$V_{\mathrm{d}}^2 = u_{\mathrm{FF}} + u_{\mathrm{FB}} \quad (12)$$

Here, since there is a possibility of melting the actuator when it is heated excessively, as the melting prevention measure, the following saturation function is applied [11].

$$V_{\mathrm{in}} = \begin{cases} V_{\max} \text{ if } V_{\max}^2 < V_{\mathrm{d}}^2 \\ |V_{\mathrm{d}}| \text{ if } V_{\min}^2 < V_{\mathrm{d}}^2 \leq V_{\max}^2 \\ V_{\min} \text{ if } 0 \leq V_{\mathrm{d}}^2 \leq V_{\min}^2 \end{cases}, \quad (13)$$

where $V_{\max}$ denotes the maximum input voltage.

III. Experimental Setup

In order to implement the proposed controller, parameter identification experiments for the proposed models are performed to estimate each parameter beforehand. In the experiments, a fishing line made of nylon (TORAY, Silver scale No. 6, diameter 0.403 [mm], length 25 [mm]) and enameled wire (diameter 0.1[mm], enamel coating thickness $0.005 \sim 0.012$ [mm], total resistance 0.8 [Ω]) are used as the material of the TPF actuator. The microscopic photo of the TPF actuator is shown in Fig. 2. In order to prepare the actuator, a twist is applied to the lower end of the nylon yarn with a weight attached just before coiling, and heat treatment is performed at 180 [deg-C] for one hour in

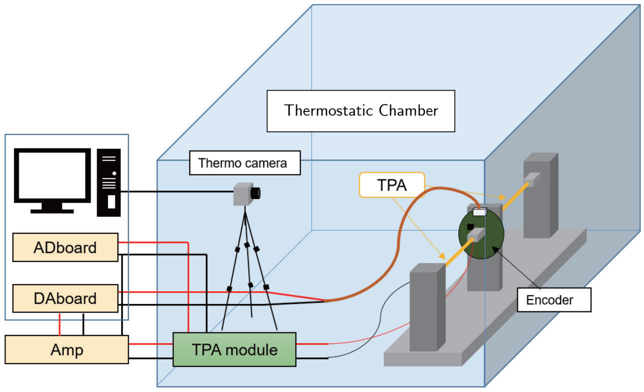

Fig. 3. Overall System of the experimental setup.

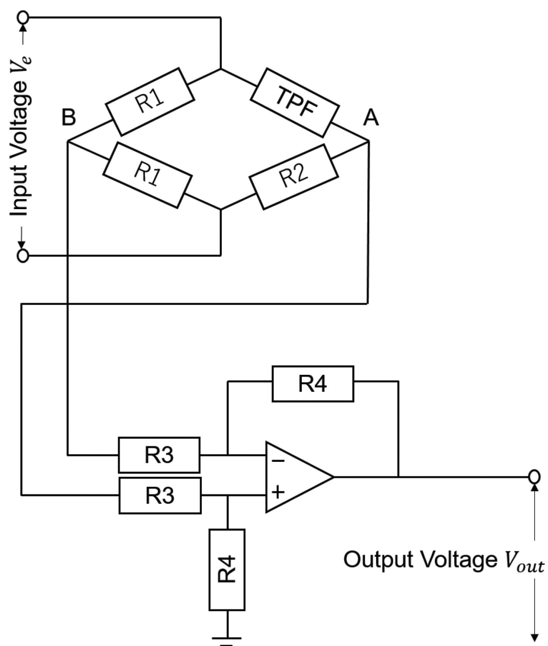

Fig. 4. Sensing module.

an oven (AS ONE OFW-300B). Thereafter, an enameled copper wire (diameter 0.1 [mm]) is wound around the actuator as a heater.

A. Prototype of the Experimental Setup

A prototype of the experimental setup is shown in Fig. 3. As it can be seen from the figure that both the ends of the antagonistically arranged TPF actuators are fixed at the base, and the rotational angle of the center joining point is used as the output, and its angle is measured by an encoder (TAR-200 manufactured by Technohands Co., Ltd.). The change in resistance value of the TPF actuator is taken out as a potential difference by a bridge circuit based on the one-gauge method, and its signal is amplified with an operational amplifier (LM258AP made by TEXAS INSTRUMENTS), and then the amplified analog signal takes in using the AD board (PEX 321216 made by Interface). Hereafter, the bridge circuit and the operational amplifier except for the TPF actuator itself is referred to as the sensing module (see Fig. 3). The resistance value R_{TPF} of the heating wire that adds Joule heat to the TPF actuator is given as follows:

$$R_{\text{TPF}} = \frac{R_4 V_e - 2R_3 V_{\text{out}}}{2R_3 V_{\text{out}} + R_4 V_e} R_2, \tag{14}$$

where V_e denotes the input voltage to the sensing module, V_{out} denotes the output voltage of the operational amplifier, and $R_1 \sim R_4$ denote each resistance value used for the bridge circuit. Equation (14) indicates that R_{TPF} can be obtained from each resistance value and output voltage only. It is assumed that the main body of the TPF actuator and the heating wire are in sufficient contact with each other and there are no dynamics interposed therebetween. Namely, the temperature of the heating wire is regarded as the temperature of the TPF actuator. The temperature of the TPF actuator is measured with a thermographic camera (PI 230 made by Optris), whose measured value is used just for the parameter estimation and not used in the controller at all.

The control input voltage is output from the DA board (PEX 340416 made by Interface) and is amplified by an amplifier (PMX35-3A made by KIKUSUI). The sampling period of the control input is set to be 10 [ms], and the initial condition of each experiment is set so as to be always constant as much as possible. Also, in order to eliminate the influence of disturbance caused by the change in environmental temperature, the entire experiment system is placed in a thermostatic chamber (A4201 made by IKUTA) and the ambient temperature is kept constant at 25 [deg-C]. All the experiments are conducted in the thermostat chamber. It is because when the ambient temperature changes, all the identified parameters would be changed.

TABLE I
INPUT VOLTAGES FOR THE ESTIMATION

Input Voltage[V]				
4.0	3.6	3.0	2.4	1.8

B. Parameter Estimation Experiments

For parameter estimation, the following step input is given as an input. The following step input is given to only one of the antagonistically arranged TPF actuators, and the opposing TPF actuator is used to generate a reaction force as a passive torsion spring.

$$V_e = \begin{cases} V_{\text{ref}} & \text{if } 5.0 < t < 40.0 \\ V_{\text{min}}(= 0.1) & \text{otherwise} \end{cases} \tag{15}$$

Here, since there are five parameters in the resistance to the change in temperature model, five types of reference voltages V_{ref} are given and three trials are performed for each voltage. In order to estimate each parameter from the measured data, the Generalized Reduced Gradient method is used. The five types of the reference voltage are shown in Table I, and the estimated parameters are shown in Table II. Also, the design parameter τ is set to be 0.7 [s].

IV. ANGLE TRAJECTORY TRACKING CONTROL EXPERIMENTS

In order to evaluate the performance of the proposed controller, the trajectory tracking control experiment is performed

TABLE II
ESTIMATED PARAMETERS ON EACH MODEL

a_1	a_2	a_3	Fitness [%]
0.98592	5.0268	4.9901	99.99

Resistance to temperature model

b_1	b_2	b_3	b_4	b_5	Fitness [%]
0.99682	0.0	0.01463	0.06868	0.09	99.99

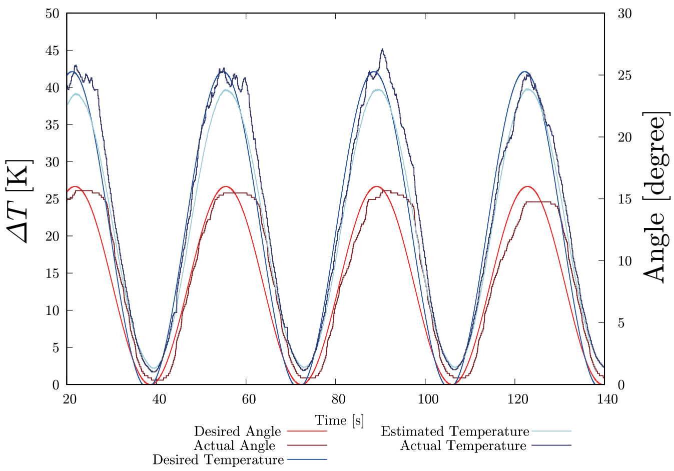

Fig. 5. Transient response of the rotational angle of the TPF actuator in the case where the frequency f of the desired trajectory is 0.03 [Hz] and the conventional PI-type feedback controller is used.

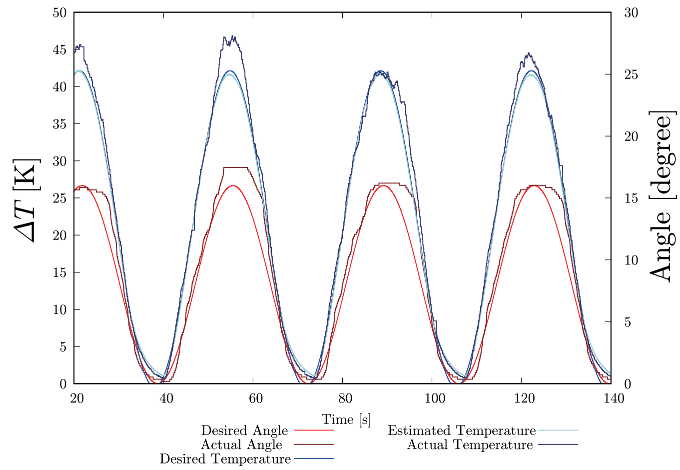

Fig. 6. Transient response of the rotational angle of the TPF actuator in the case where the frequency f of the desired trajectory is 0.03 [Hz] and the proposed controller is used.

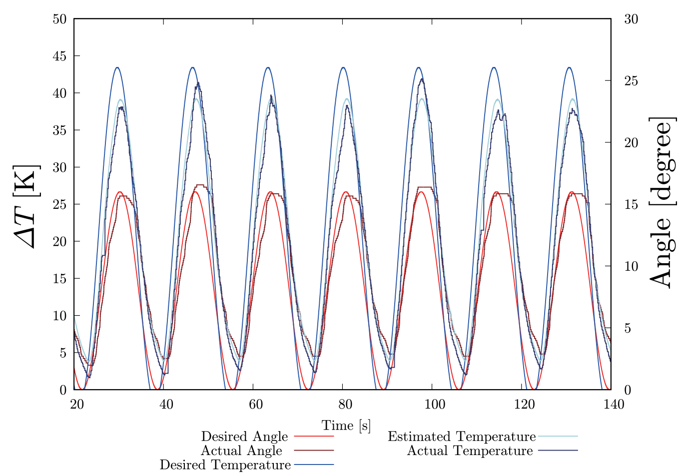

Fig. 7. Transient response of the rotational angle of the TPF actuator in the case where the frequency f of the desired trajectory is 0.06 [Hz] and the conventional PI-type feedback controller is used.

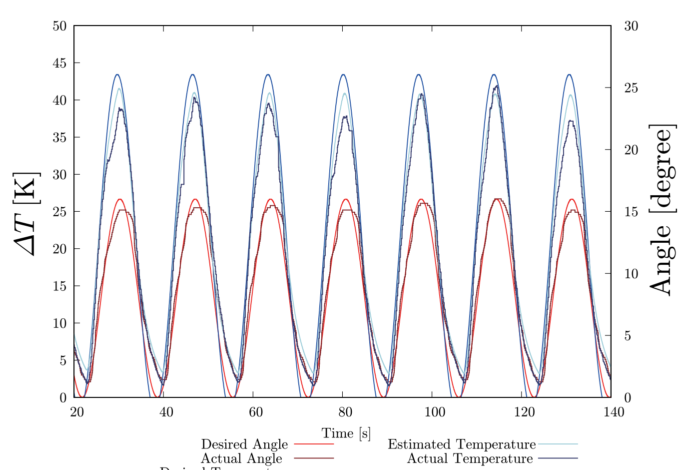

Fig. 8. Transient response of the rotational angle of the TPF actuator in the case where the frequency f of the desired trajectory is 0.06 [Hz] and the proposed controller is used.

using the proposed controller with previously determined model parameters. The desired time-dependent angle trajectory is designed as follows:

$$\theta_{\rm d}(t) = \begin{cases} 0 & (0 \leq t < 5.0) \\ -8\cos 2\pi f(t-5.0) + 8 & (5.0 \leq t), \end{cases}$$

where two types of the input frequency ($f = 0.03,\ 0.06$ [Hz]) are examined by each. Although we know that taking all range of the frequency response is the best way to evaluate the control performance, it is difficult to investigate experimentally. Therefore, in this study two typical frequency responses are examined, one is a relatively lower one (0.03 [Hz]) and the other is a relatively higher one (0.06 [Hz]). The higher frequency 0.06 [Hz] is almost the maximum responsively frequency of the actuator that can be performed under natural cooling. Also, each feedback gain is set to be $K_p = 1.4$, $K_i = 0.14$ which is fully adjusted huristically beforehand, and the maximum input voltage $V_{\max}$ is set to be 4.0 [V]. Another trajectory tracking experiment using only the feedback control ($V_{\rm d}^2 = u_{\rm FB}$) is also performed for the comparison with the proposed controller. The periodic response of the angle control is shown in Figs. 5∼8, and the Root-Mean-Square (RMS) error value of each trial is shown in Table III. As you can see these figures and table, the angular trajectory tracking error is obviously reduced when using the proposed controller. In particular, it is clear from these figures that the phase-lag in the cooling phase, which seriously affects to the tracking performance in the feedback control, can be reduced by the proposed controller. In addition, it improves the trajectory traceability at

TABLE III
RMS ERROR IN EACH EXPERIMENT

	$f = 0.03$ [Hz]	$f = 0.06$ [Hz]
feedback control	1.955	2.787
Proposed control	1.286	1.262

each peak (the maximum value and the minimum value) of the desired trajectory when using the proposed controller. However, there still remains a delay in tracking the angle at the flexion point that changes from heating to cooling. There is a possibility to be able to reduce the delay by activating an antagonistic actuator simultaneously as described in Suzuki *et al.* with TCPF actuator [11].

From the above results, it can be confirmed that the proposed controller is effective to reduce the phase-lag when tracking an angular trajectory.

V. DISCUSSION

A. Response Performance

In all the experiments, a sampling time of the controller is much enough for the TPF actuator (100 [Hz]), but the higher input frequency 0.06 [Hz] is very close to the limit of cooling rate due to a natural cooling method. Namely, the cooling phase cannot be faster even if the sampling time is set to be shorter when using the only one-side TPF actuator. However, since the proposed system has the antagonistically driven mechanism, there is a possibility to improve the response of the cooling phase using the antagonistic actuator.

B. Windup Phenomenon

In order to avoid melting of the TPF actuator, the input voltage is saturated by the arbitrarily defined maximum input voltage. On the other hand, it is known that when using a PI-type feedback controller, there is a possibility that it induces a windup phenomenon when saturation occurs. However, in this letter, the integral gain is set to be small enough not to induce such a windup phenomenon. This is because the cooling rate has already been saturated and thus the response performance is not improved enough even if the integral gain is set to be high.

C. Effect of Input Saturation

It is experimentally confirmed that the square value of the input voltage seems to be proportional to the response speed. Namely, if the arbitrarily determined limitation of the input voltage is set to be larger, the transient response can be improved when the input voltage is saturated. In addition, the limitation of the input voltage seems to be proportional to the maximum angular change during heating. However, these are just experimentally shown and it would be one of the future works to clarify it theoretically.

VI. CONCLUSIONS

In this study, we proposed an angle controller of the TPF actuator by the combination of a model-based feed-forward and estimated temperature feedback with the aim of tracking a time-dependent trajectory and confirm its effectiveness. The proposed method is composed of the angle controller based on the estimated temperature feedback we have previously proposed [2] and the model-based feed-forward controller.

The proposed prototype for experiments only required the TPF actuator and the sensing module which can be composed of only four Ohm-resistors with no other expensive, hard or heavyweight devices. Namely, the proposed controller does not degrade the advantage of the TPF actuator, such as low cost, cheap, and lightweight. The experimental results demonstrated that the proposed controller can improve the trajectory tracking performance by reducing the phase-lag.

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