A temperature-dependent control technique for a highly sensitive piezoelectric actuator

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***Abstract*— This paper deals with the control of the piezoelectric tube in the presence of the variation of the temperature. Besides the hysteresis and the creep nonlinearities, and the badly-damped oscillations, the piezoelectric tube is highly-sensitive to the variation of the temperature. This variation impacts considerably the global model of the actuator and induces the change in its resonant frequencies. To handle the variation of the actuator model we propose the combination of the classical Proportional-Integral structure with the switching strategy. The proposed control strategy is applied to the X-axis of the piezoelectric tube. The simulation and the experimental results prove the efficacy of the proposed control strategy to maintain the good performances of the closed-loop system, in the presence of temperature variations.**

I. INTRODUCTION

Piezoelectric actuators are prized to handle tasks demanding a very high degree of precision and resolution. These tasks include mainly micro/nano assembly [1], [2] and manipulation [3], positioning [4] and sensing [5]. The increasing use of the piezoelectric based actuators in such tasks is namely due to their sub-nanometric resolution, the rapidity of action (large bandwidth which can attain 1kHz), the ease of manufacturing, alimentation and integration in positioning or manipulation systems.

However, piezoelectric based actuators are typified by the badly-damped oscillations due to their cantilevered structure, the hysteresis and the creep nonlinearities, and are highly sensitive to the variation of the temperature. These effects affect considerably the aforementioned excellent properties of these actuators. To maintain the good working performances the control of piezoelectric actuators is necessary.

The control of badly-damped oscillations, the hysteresis and the creep nonlinearities has been widely studied. The proposed control laws include feedforward [6], [7], [8], feedback [9] or a combination of feedforward and feedback techniques [10], [11], [12]. The feedforward control is mainly used to increase the degree of packageability of the control schemes in micro/nano-applications, where the space to install feedback sensors is limited. However, feedforward control does not ensure the robustness when the actuator is subjected to the disturbances or the model uncertainty. Furthermore, various feedback techniques are used to control piezoelectric actuators. The most used are H_∞ [13], [14], [15], Linear Quadratic Gaussian (LQG) [16], [17], Adaptive Control techniques [18], [19], [20], Internal Model Control (IMC) [21], [22] and Proportional-Integral-Derivative structure [25], [23], [24].

The aforementioned techniques have been successfully applied to the control of badly-damped oscillations, the hysteresis and the creep. However, the control of the temperature effect is still to be established. In fact, the model of the actuator changes depending on the temperature around the actuator. It has also been proven that the variation of the temperature induces the shift of the resonant frequencies of the actuator [26]. For relatively small variations of the temperature, H_∞ or adaptive control techniques can be successfully applied. For large temperature variations, the modification of the actuator model becomes important that the control laws have to consider multiple models for the actuator.

In this paper, we propose the use of the classical Proportional-Integral structure to control the effect of the temperature variation on the piezoelectric tube. To take into account the variation of the piezoelectric tube model, the Proportional-Integral structure is combined with the switching strategy. It is worth to mention that a control structure other than the Proportional-Integral can be used. The choice of the Proportional-Integral structure is based on two reasons: (1) the Proportional-Integral structure is easy to synthesize and easy to implement; (2) it has been demonstrated that high gain Proportional-Integral controllers are able to handle hysteresis and creep phenomenons [12], [27], [28] (hence, no additional control scheme needed for the hysteresis or for the creep).

To validate the proposed control strategy we use the piezoelectric tube actuator (called also simply piezotube), very known in scanning probe microscopy. This actuator permits to achieve spatial positioning by providing deflections along three axis X, Y and Z. However, the characterization, the modeling, the simulations and the control dealt in this paper are limited to one axis of the piezotube (X-axis). The extension of the proposed control technique to multivariable control is part of our future works.

The paper is organized as follows. In section-II we present the piezotube, its working principle and the experimental setup. In section-III we characterize the effect of the temperature variation on the dynamics of the X-axis of the piezotube and we identify dynamic models corresponding to each characterization temperature. Section-IV is devoted to the design and the simulation of the Proportional-Integral control of the temperature effect. The experimental implementation and

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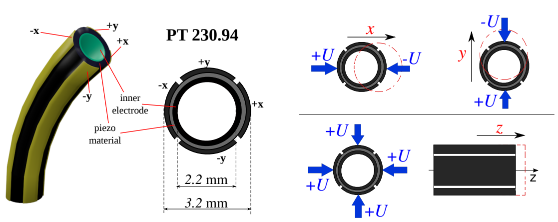
results of the proposed control strategy on the piezotube are presented in section-V and the conclusions and perspectives are drawn in section-VI.

II. Presentation of the piezoelectric tube and experimental setup

A. Presentation and working principle of the piezotube

The proposed control strategy has been validated on the PT 230.94 piezotube, fabricated by *Physik Instrumente* company. This tube has 30 mm of length, 3.2 mm of outer diameter and 2.2 mm of inner diameter (1 mm of thickness). It is made of PZT material coated by four external electrodes +x, -x, +y and -y, and one inner electrode (Fig. 1a). Voltages U_x and U_x (U_y and U_y) can be applied on +x and -x (+y and -y) electrodes in order to obtain the tube deflections along X-axis (along Y-axis). To obtain the elongation of the tube along Z-axis, the voltage U_z is applied simultaneously on the four external electrodes (Fig. 1b).



(a) (b)

Fig. 1: Description and working principle of the piezoelectric tube. (a) Perspective and top views of the tube, (b) Working principle: application of voltages U and $-U$ in order to get deflections along X, Y and Z axis.

B. Experimental setup

The experimental setup is composed of:

- the PT 230.94 piezotube;
- three optical displacement sensors;
- the computer with *Matlab/Simulink* software;
- a dSPACE board;
- and the voltage amplifiers.

The optical sensors and the piezotube are enclosed inside a dedicated temperature controlled room. This room has a specific temperature measurement system which permits to record the evolution of the temperature inside the room.

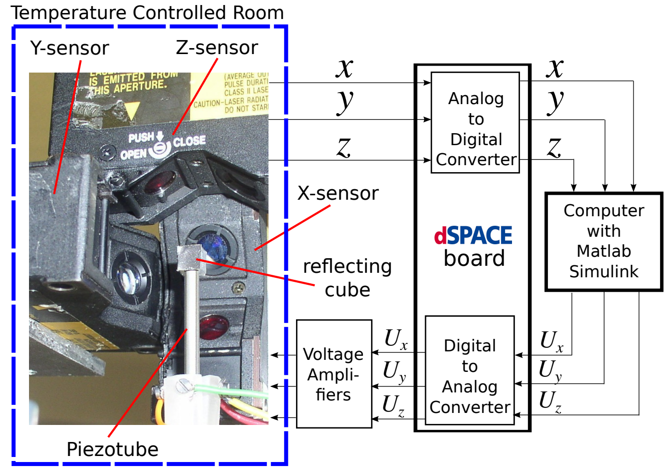


Fig. 2: The description of the experimental setup.

The displacement sensors and the voltage amplifiers are connected to the computer through the dSPACE-1103 board which ensures the digital-analog conversion. The operating voltage range of the PT230.94 is ±250V for a deflection of 35μm. Hence, two voltage amplifiers are used to amplify the dSPACE board output voltages, for which the maximum range is about 10V. To allow a linear measurement of the tube deflections by the optical sensors (which is not possible due to the tubular shape of the piezotube), a small cube with perpendicular and flat sides is placed on the top of the tube. The used optical sensors are the LC-2420 (fabricated by *Keyence* company), which have 10nm resolution, a bandwidth of 50kHz with a working temperature range between 0 and 40°C.

III. Characterization of the temperature effect

The characterization has been carried out for the temperature range between 25°C and 35°C, with an increment of 0.5°C, i.e $T_{i+1} = T_i + 0.5$ with T_0=25°C. For each T_i, the actuator dynamics are characterized and modelled. We have also characterized the effect of the temperature on the hysteresis and the creep.

The characterization of the dynamics is performed from the step response of the actuator. To do this, a step input $U = 200$V is applied to x electrodes of the piezotube and the deflection x is recorded for a very short time (20ms in this paper) following the application of U. The obtained step responses for each temperature T_i are represented in Fig. 3 (only some step responses are represented for the sake of clarity).

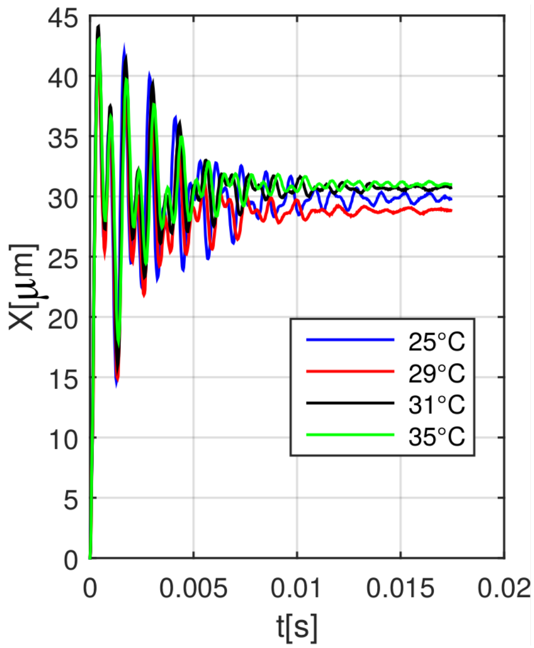


Fig. 3: The experimental characterization of the step responses for X-axis at different temperatures.

The results in Fig. 3 show that the step responses of the actuator change with the temperature. We notice also the impact of the temperature variation on the stiffness of the actuator.

Fig. 4 represents the characterization results of hysteresis, characterized by using a sine wave of amplitude 200V at a frequency of 0.1Hz. We notice that the shape of the hysteresis curves does not change but the inclination of the curves (which corresponds to the stiffness of the actuactor) changes. This remark was also noticed in other works, for instance in [29], [30].

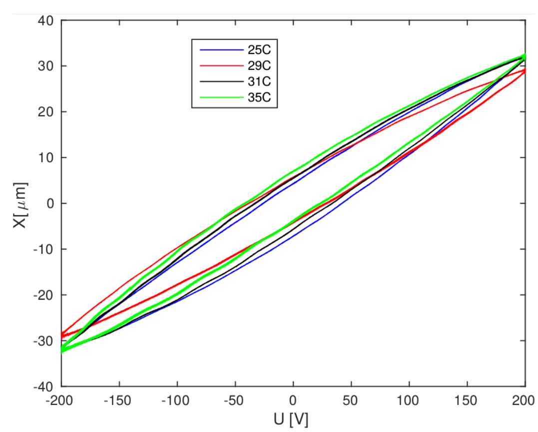


Fig. 4: The experimental characterization of hysteresis at different temperatures.

Fig. 5 represents the creep curves at various temperatures, characterized by using a step voltage of 200V. These results show that the variation of the temperature impacts also the amount of the creep.

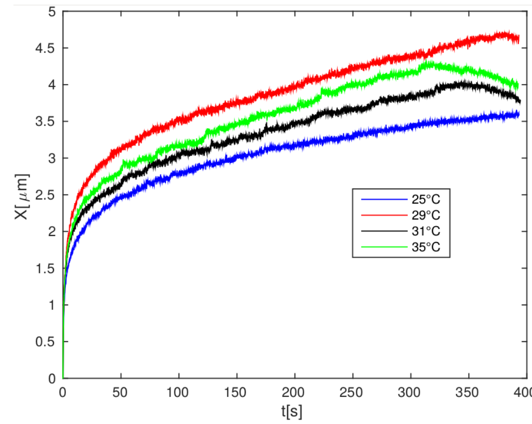


Fig. 5: The experimental characterization of the creep at different temperatures.

To obtain the dynamic models corresponding to each temperature (transfer functions $G_{T_i}(s)$), the *Identification Toolbox of Matlab* [31] is applied to the step responses of Fig. 3.

The Bode diagrams for the obtained $G_{T_i}(s)$ are represented in Fig. 6a, where we notice the variation of the dynamics of the actuator when the temperature varies. We notice also that the variation of the temperature shifts the resonant frequencies of the actuator. This resonant frequency shift is represented by Fig. 6b. This figure shows that a change of the temperature from 25°C to 35°C leads to a shift of 100Hz of the first and the second resonant frequencies.

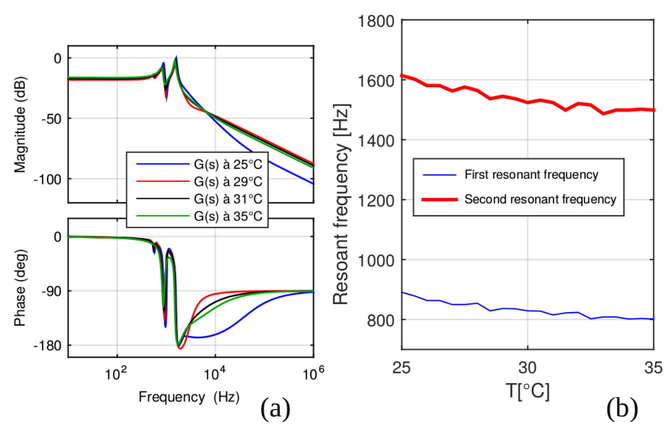


Fig. 6: The characterization of the effect of the temperature on the actuator dynamics.

IV. Proportional-Integral control of the temperature effect

The characterization results in the previous section prove that the piezotube is highly sensitive to the variation of the temperature. The dynamic model of the actuator changes with the temperature and the control law has to take into account this change. In this section, we propose a control scheme composed of the Proportional-Integral controller combined with the switching strategy. As stated in Introduction, the Proportional-Integral controller is chosen due to its capacity to handle badly-damped oscillations of the actuator but also the hysteresis and the creep nonlinearities. The switching strategy is added to the Proportional-Integral controller in order to take into account the variation of the actuator model.

First, we show that a single controller designed at the nominal temperature (at T=25°C) does not ensure some good working performances when the temperature varies. In this paper, the target performance is the rapidity of the closed-loop system.

After showing the limitation of using one single controller, we introduce the switching strategy, allowing to implement different Proportional-Integral controllers and to select the appropriate controller depending on the temperature measured around the actuator.

The classical form of the Proportional-Integral is

$$K(s) = k\left(1 + \frac{1}{\tau}\frac{1}{s}\right), \quad (1)$$

where k and τ are the proportional gain and the time response of the controller, respectively. For the Proportional-Integral controller designed at the temperature T_i (based on the model $G_{T_i}(s)$) we use the form

$$K_{T_i}(s) = k_{T_i}\left(1 + \frac{1}{\tau_{T_i}}\frac{1}{s}\right). \quad (2)$$

Based on the dynamic nominal model $G_{25}(s)$ (the model of the system at T=25°C), the controller parameters $k_{25} = 671 \times 10^{-6}$ and $\tau_{25} = 2.25 \times 10^{-7}$s have been obtained. The controller $K_{25}(s)$ has then been implemented as on the scheme of Fig. 7, and the closed-loop system has been simulated for different models $G_{T_i}(s)$.

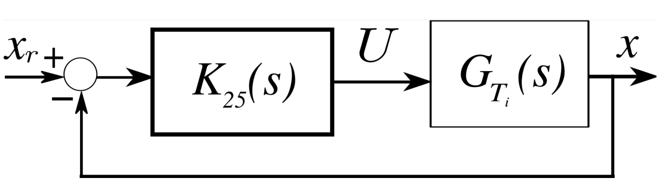


Fig. 7: The implementation scheme of the Proportional-Integral controller with the actuator subjected to the variation of the temperature.

The obtained step responses are represented in Fig. 8.

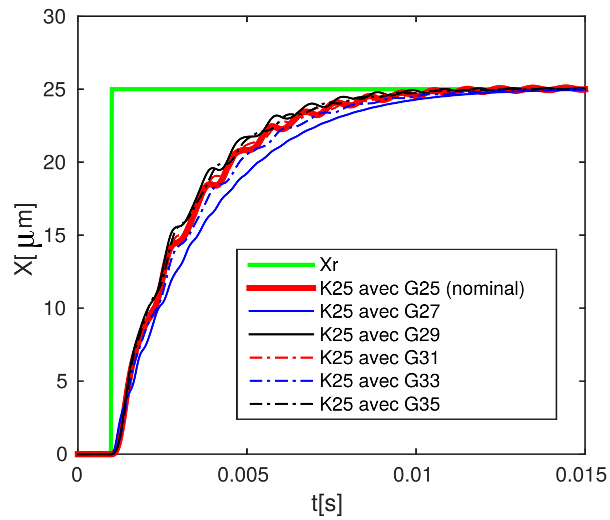


Fig. 8: Simulations of the step responses when only the nominal controller $K_{25}(s)$ is used.

We notice that, if only $K_{25}(s)$ is used, the system tends to be slow at some temperatures. The time responses corresponding to the step responses in Fig. 8 are in Tab. I, where we notice that the time responses at temperatures $27, 31$ and 33°C are greater than the time response of the nominal system ($t_r = 6.3$ms).

TABLE I: The time responses for the controlled system when only $K_{25}(s)$ is used.

T [°C]	**25**	27	29	31	33	35
t_r 95% [ms]	**6.3**	7.8	5.6	6.6	6.9	6.0

To ensure the rapidity of the controlled system compared to the nominal system, we have introduced the switching controller strategy. Therefore, for each model $G_{T_i}(s)$ a Proportional-Integral controller $K_{T_i}(s)$ is calculated. Each controller is calculated with an objective to render the closed-loop faster than the controlled nominal system. Based on the characterized dynamics $G_{T_i}(s)$, the obtained parameters k_{T_i} and τ_{T_i} of the controllers $K_{T_i}(s)$ are represented in Tab. II (for six selected temperatures).

TABLE II: Parameters for the controllers $K_{T_i}(s)$.

T [°C]	25	27	29	31	33	35
k_{T_i} [$\times 10^{-6}$]	671	827	613	665	720	632
τ_{T_i} [$\times 10^{-7}$s]	2.25	2.00	2.10	2.00	2.00	2.00

To simulate the effect of the combination of Proportional-Integral and the switching strategy, the controllers $K_{T_i}(s)$ and the models $G_{T_i}(s)$ have been implemented in *Matlab/Simulink* following the scheme of Fig. 9. The controller and the model selection blocks permit to choose the controller and the model corresponding to the temperature T.

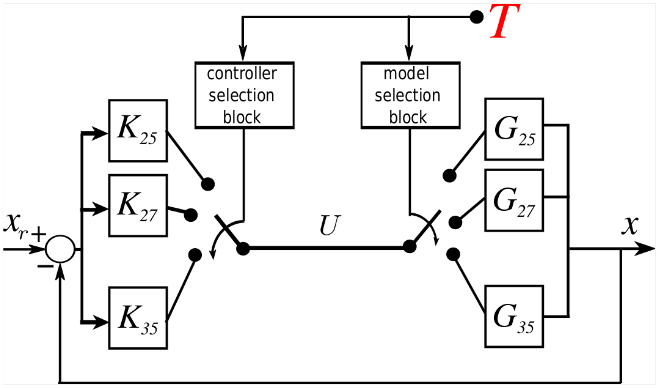


Fig. 9: The simulation scheme of the combination of the Proportional-Integral with the switching strategy.

The simulated step responses are represented in Fig. 9.

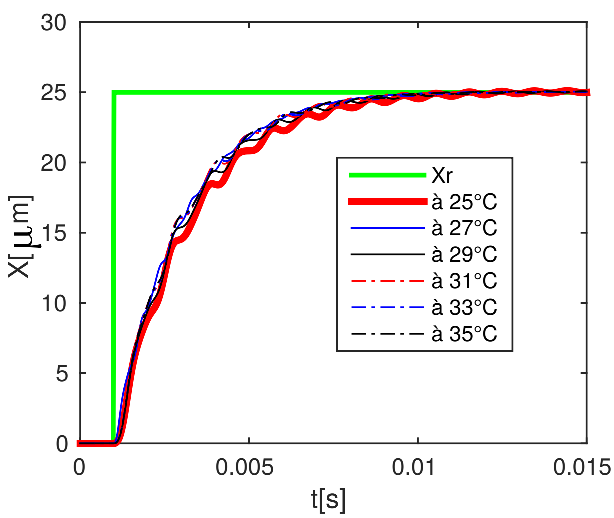


Fig. 10: The simulated step responses for the system controlled by the Proportional-Integral controllers combined with the switching strategy.

The time responses of the step responses of Fig. 10 are represented in Tab. III.

TABLE III: Time responses when PI is combined with the switching strategy.

T [C]	**25**	27	29	31	33	35
t_r 95% [ms]	**6.3**	5.6	6.3	5.7	5.8	5.8

By comparing the step responses of Fig. 8 and Fig. 10 (tables Tab. I and Tab. III), we notice that the combination of Proportional-Integral and the switching strategy allowed to ensure the speed of the system for all the considered temperatures.

V. Experimental implementation of the Proportional-Integral combined with the switching strategy

After the validation of the proposed control strategy by simulations, we have implemented the controllers $K_{T_i}(s)$ and tested them on the piezotube. The implementation is performed by following the scheme of Fig. 11.

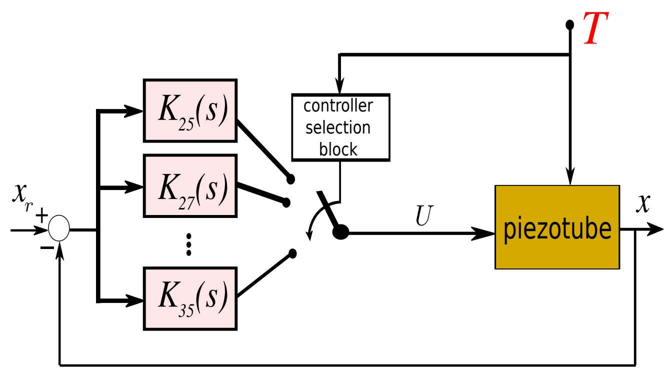


Fig. 11: The experimental implementation scheme of the Proportional-Integral combined with the switching strategy.

The temperature around the piezotube has been varied and at each temperature T_i a step reference input $x_r = 20\mu$m has been applied. The obtained step responses are represented in Fig. 12 for the selected temperatures. We notice that the proposed technique ensures the rapidity of the closed-loop system compared to the nominal system, in spite of the variation of the temperature around the actuator.

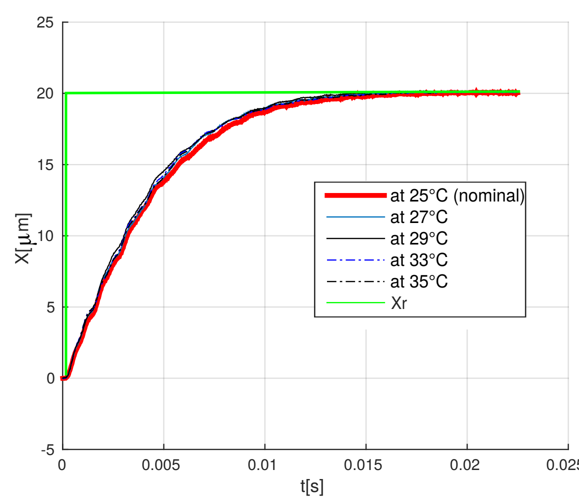


Fig. 12: Experimental step responses when the Proportional-Integral is combined with the switching strategy.

VI. Conclusions and Perspectives

This paper dealt with the control of the highly-sensitive piezotube in presence of the variation of the temperature. The characterization results have shown that the dynamic model of the actuator changes with the variation of the temperature. To take into account the variation of the actuator model we have proposed the combination of the Proportional-Integral controller and the switching strategy. The Proportional-Integral controller has been chosen due to its ease of calculation and its ability to handle the hysteresis and the creep phenomenons which affect the piezotube. The simulation and experimental results prove the efficacy of the proposed control strategy to ensure good closed-loop performances in the presence of the temperature variation. Nevertheless, the control strategy in this paper has been applied only on the X-axis of the piezotube. Future works will deal with the extension of the proposed control strategy to the simultaneous control of the X,Y and Z-axis of the piezotube. Also, the proposed control technique may induce some vibrations and a chattering behaviour, due to the switching action. In our future works, other techniques able to counteract these drawbacks, such as the use of Schmitt trigger, will be integrated in the proposed control scheme.

ACKNOWLEDGMENT

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