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IFAC-PapersOnLine 49-21 (2016) 354–360

Characterization and modeling of the temperature effect on the piezoelectric tube actuator

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Abstract: This paper deals with the characterization and the modeling of the temperature effect on the piezoelectric tube actuator. Besides the sensitivity to the variation of the temperature, this actuator is characterized by the hysteresis and the creep non-linearities, the badly-damped vibration and the cross-couplings between its three axis. First, the characterization results of the sensitivity of this actuator to the temperature variation (thermo-mechanical deflection) are presented. Then, the effect of the temperature on the hysteresis, the creep, the vibration and the cross-couplings is presented. Finally, from the existing electro-mechanical model of the deflection of the piezoelectric actuators, the temperature-dependent model is proposed. The validation results on one of the piezoelectric tube axis demonstrates the efficacy of the proposed modeling approach.

Keywords: Characterization, modeling, temperature effect, hysteresis, creep, vibration, piezoelectric tube.

1. INTRODUCTION

Piezoelectric actuators are very known in various applications at micro/nano-scale. These applications include nano/micro-positioning (1; 2; 3), -manipulation (4; 5), -assembly (6; 7; 8), etc. The popularity of these actuators is mainly due to the good performances that they offer: the nanometric resolution, the high resolution (more than 1kHz possible), the facility of alimentation and integration in microsystems, etc. From a functional point of view, piezoelectric actuators can be categorized into two groups. The first group includes mono-axis piezoelectric actuators, designed to provide deflections along one direction (e.g. the unimorph cantilevers and piezostacks). Mono-axis piezoelectric actuators are used mainly for manipulation and assembly tasks. The second group concerns the multi-axis piezoelectric actuators, designed to bend along different directions (e.g. the piezoelectric tube called also piezotube). Multi-axis actuators are mainly used for spatial positioning tasks, such as scanning probe microscopy (9).

Despite these advantages, piezoelectric actuators exhibit the hysteresis and the creep nonlinearities, the badly-damped vibration due to their cantilevered structure and the cross-coupling effect for multi-axis actuators such as the piezotube. In addition to the aforementioned drawbacks, piezoelectric material are very sensitive to the variation of the temperature. Consequently, the good working performances of the piezoelectric actuators are compromised when they are working in a temperature varying environment.

The characterization, the modeling and the control of the hysteresis, the creep and the badly-damped vibration have been widely studied, for mono-axis (10; 11; 12; 13) and for multi-axis (14; 15; 16; 17) piezoelectric actuators. However, the issue of the temperature effect is still to be established.

In (18), the effect of the temperature effect on a piezoelectric stack is studied but the study is limited to its impact on the hysteresis. In (19), the temperature effect on the hysteresis, the creep and the vibration was characterized but not modelled. In addition, the characterization in the aforementioned works concerned the case of mono-axis actuators and the issue of the cross-coupling effect has not been addressed. In (20; 21; 22), the impact of the temperature variation on the piezoelectric coefficients has been evaluated. The modeling strategy based on this study leads to physical models of the piezoelectric actuators. The physical models permit to have more information about the actuator. However, they represent a high degree of parametrization, which leads to complex identification and difficult extension to multivariable modeling.

In this paper, we characterize the temperature effect on the piezotube. In addition to the hysteresis, the creep and the vibration, the effect of temperature on cross-couplings is also evaluated. The characterization process is performed inside a dedicated temperature controlled room. To model

⋆ This work is supported by the national ANR-JCJC C-MUMS-project (National young investigator project ANR-12-JS03007.01: Control of Multivariable Piezoelectric Microsystems with Minimization of Sensors). This work has also been supported by the Labex ACTION project (contract "ANR-11-LABX-01-01").

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2016.10.580

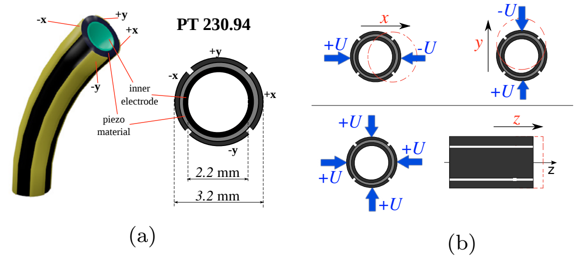

Fig. 1. Description and working principle of the piezoelectric tube. (a) Perspective and top views of the tube, (b) Working principle: application of voltages U and $-U$ in order to get deflections along X, Y and Z axis.

the temperature effect we use the phenomenological model (input-output or black box model) of the deflection of a piezoelectric actuator. Contrary to the physical models, the phenomenological models have the advantage of being simple and easy to identify. First, we propose the mono-variable temperature-dependent model which includes the thermo-mechanical effect, the hysteresis, the creep and the vibration. Then, after its identification and validation, its extension to the multivariable modeling is proposed. The proposed multivariable model is adapted to systems with the same number of inputs and outputs (fully actuated systems) but also to the systems with a different number of inputs and outputs (under or over actuated systems).

This paper is organized as follows. Section II presents the piezoelectric tube, its working principle and the experimental setup. In section III, we present the experimental procedure, the characterization results and discussions. Section IV is devoted to the modeling of the temperature effect. Finally, conclusions and perspectives are drawn in section V.

2. PRESENTATION OF THE PIEZOELECTRIC TUBE AND EXPERIMENTAL SETUP

2.1 Presentation of the piezoelectric tube and its working principle

The actuator used for experimentations in this paper is the PT 230.94 piezoelectric tube (called also piezotube), fabricated by *Physik Instrumente* company. Its presentation and working principle are described in Fig. 1. It is made of the 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 bend the tube along X-axis (along Y-axis). To obtain the elongation of the tube along Z-axis, the same voltage U_z is applied simultaneously on the four external electrodes (Fig. 1b).

Hence, from the modeling point of view, the piezoelectric tube corresponds to a multivariable system, with three inputs (voltages U_x, U_y and U_z) and three outputs (deflections x, y and z).

2.2 Experimental setup

The experimental setup (Fig. 2) is composed of a piezoelectric tube, a computer with *Matlab/Simulink* software, three optical displacement sensors and voltage amplifiers.

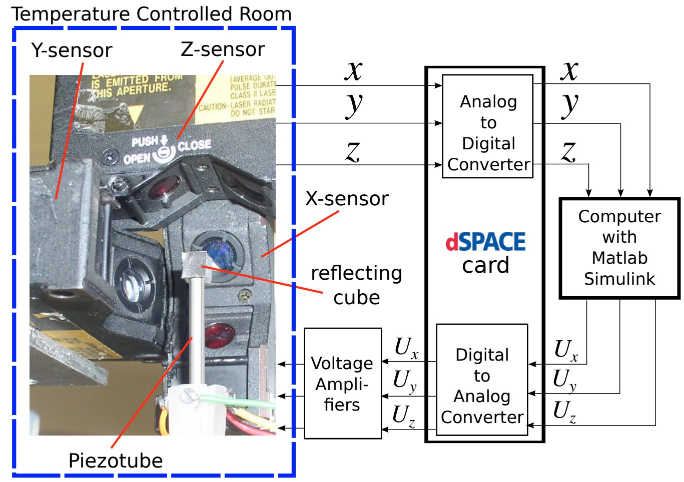

Fig. 2. The description of the experimental setup.

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

Both displacement sensors and voltage amplifiers are connected to the computer through a dSPACE-1103 board. 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 . The tube deflections are measured by using the LC-2420 displacement sensors (fabricated by *Keyence* company). A small cube with perpendicular and flat sides is placed on the top of the tube to allow a linear displacement measurement by optical sensors (which is not possible with the tubular shape of the piezotube). The LC-2420 sensors have 10nm resolution, a bandwidth of 50kHz with a working temperature range between 0 and 40°C.

3. CHARACTERIZATION OF THE TEMPERATURE EFFECT

3.1 Characterization procedure

The characterization has been carried out for the temperature range between 23°C to 39°C, with an increment of 0.5°C, i.e $T_{i+1} = T_i + 0.5$ with T_0=23°C.

For each T_i, the following effects are characterized:

- the sensitivity of the actuator to the variation of the temperature (the thermo-mechanical deflection);
- the hysteresis, the creep and the badly-damped vibration.

3.2 Thermo-mechanical deflection

The evaluation of the thermo-mechanical deflection is performed as follows. After taking all the required characterizations at T_i, the voltage applied to the actuator is put to zero and the position of the tip of the actuator y_{T_i} is recorded. Then, the temperature is increased from T_i to T_{i+1}. When the temperature reaches T_{i+1} the position of the tip ($y_{T_{i+1}}$) is recorded again and compared to y_{T_i}. This comparison gives the sensitivity of the actuator to