Simultaneous Suppression of Badly-Damped Vibrations and Cross-couplings in a 2-DoF Piezoelectric Actuator, by using Feedforward Standard H_∞ approach

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ABSTRACT

This paper deals with the feedforward control of vibrations in a 2-axis piezoelectric actuator devoted to precise positioning. The actuator is very prized for high precision spatial positioning applications, but its positioning capability as well as the stability of the final tasks are compromised by badly-damped vibrations, especially during high-speed positioning operation. In addition to these vibrations, the presence of strong cross-couplings between different actuator axis poses challenge in the feedforward control scheme. This paper proposes a bivariable feedforward standard H_∞ approach to suppress the vibrations in the direct transfers and to reduce the amplitudes of the cross-couplings. The proposed approach is simple to handle and easy to implement, comparatively to the commonly used techniques for oscillations suppression. Experimental tests demonstrate the efficiency of the proposed approach.

Keywords: Multi-axis piezoelectric actuators, Vibrations, Cross-couplings, Multivariable feedforward control, Standard H_∞ approach.

1. INTRODUCTION

Multi-axis piezoelectric actuators are very known in spatial positioning tasks, especially in micro/nano scale applications [1,2]. However, the positioning precision of these actuators and the stability of the final tasks are compromised by badly-damped vibrations and by the cross-couplings between the actuators axes [3]. Feedback control appears to be the best way to handle these problems but the use of closed loop control techniques in micro/nano scale is limited by the difficulty to integrate feedback displacement sensors. On the one hand, embeddable sensors (capacitive, inductive, etc) do not have the required performances (low noise, high resolution and accuracy, low environmental sensitivity, bandwidth, etc). On the other hand, sensors with the necessary performances such as optical sensors are very spacious, which makes their installation difficult, especially for multi-axis actuators where a high number of sensors is required [4,5]. Feedforward control techniques have been seen as a good solution to that problem [1,4–6].

In the literature, inverse-dynamics [6,7] and input-shaping techniques [4,5,8,9] rank among the most used techniques for feedforward control of vibrations. However, the identification of multi-axis piezoelectric actuators may lead to nonminimum-phase and non-bicausal models, for which the inverse-dynamics control are less adapted [6]. In this paper, we propose a feedforward H_∞ approach to control a 2-axis piezoelectric actuator.

The feedforward control of piezoelectric actuators based on H_∞ approach has been used in (G. Schitter et al., 2003) [10] for a 1-DoF application. In this paper, we extend this technique to a 2-axis (2 DoF) actuator, by considering simultaneously the direct transfers and the cross-couplings. This leads to a 2-DoF compensator, able to suppress the vibrations in the direct transfers and able to reduce the amplitudes of the cross-couplings. The proposed approach allows to calculate a feedforward vibrations compensator without any need to invert the model, which is an easier and less time-consuming way than with inverse-dynamics based techniques. The experimentations carried out demonstrate the efficiency of the proposed approach.

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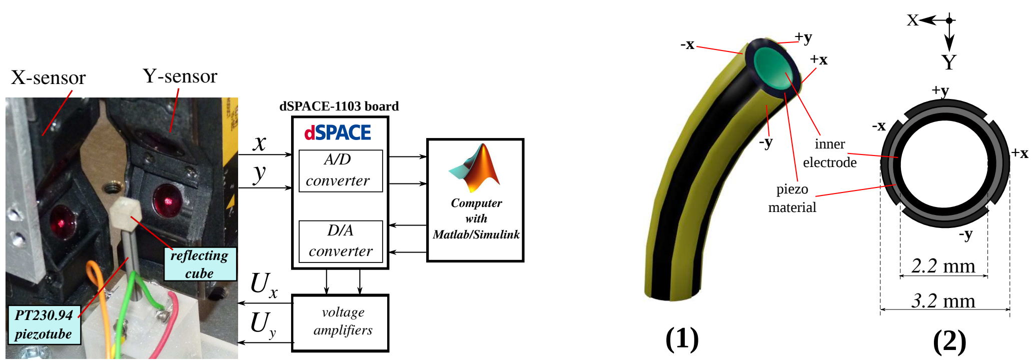
The remainder of the paper is organized as follows. Section 2 describes the experimental setup and the actuator used. Section 3 concerns the multivariable characterization and modeling of the vibrations for the 2-DoF actuator. In section 4 we use the model obtained in section 3 to calculate the 2-DoF vibrations compensator. The implementation of the obtained compensator along with the simulation and experimental compensation results are presented in section 5. Finally, section 6 concludes the paper and gives some perspectives.

2. EXPERIMENTAL SETUP

The experimental setup is represented in Fig. 1. It is composed of a piezoelectric tube, a computer with *Matlab/Simulink* software, two displacement sensors and two voltage amplifiers. Both displacement sensors and voltage amplifiers are connected to the computer through a *dSPACE-1103* board. The piezoelectric tube scanner used is the PT230.94, 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). PT230.94 is made of PZT material coated by one inner electrode (in silver) and four external electrodes (in copper-nickel alloy), commonly named +x, -x, +y and -y (Fig. 1b). 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 allow a linear displacement measurement (which is not possible with the tubular shape of the piezotube), a small cube with perpendicular and flat sides is placed on the top of the tube. The operating voltage range of the PT230.94 is $\pm 250V$ 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 $\pm 10V$. The tube deflections are measured by using LC-2420 displacement sensors (fabricated by *Keyence* company), which have 10nm resolution and a bandwidth of 50kHz. Note that these displacement sensors are used only for vibrations characterization : the proposed control approach is exclusively feedforward and these sensors are not needed for tracking.



(a) Experimental setup.

(b) Description of the piezoelectric tube. (1) : perspective view, (2) : top view.

FIGURE 1: Presentation of the experimental setup and description of the used actuator.

3. CHARACTERIZATION AND MODELING OF THE VIBRATIONS FOR THE 2-DOF SYSTEM

The system to be characterized (refer to Fig. 2) is a 2-DoF piezoelectric tube with inputs U_x and U_y voltages, and outputs x and y deflections. To characterize its vibrations , we apply first a step voltage U_x of amplitude $200V$ and we let U_y be zero. The corresponding displacements x and y are pictured in Fig. 3a,c (blue solid line). Fig. 3a shows the vibrations for the direct transfer $U_x \to x$, while Fig. 3c shows the vibrations for the coupling $U_x \to y$. Afterwards, we repeat the same operation by using a step U_y of amplitude $200V$ with U_x set to zero. The captured deflections x and y are represented in Fig. 3b,d (blue solid line). Fig. 3b represents the vibrations for the coupling $U_y \to x$, while Fig. 3d shows the vibrations for the direct transfer $U_y \to y$. From Fig. 3, we notice the presence of badly-damped vibrations in both direct and coupling transfers. The transfer function $G(s)$ to be

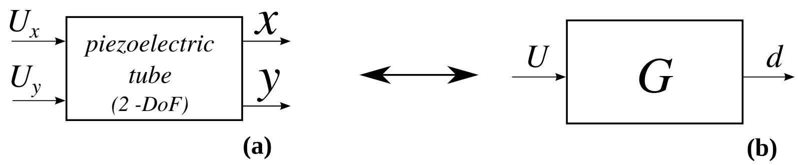


FIGURE 2: System modeling scheme. (a) : the 2-DoF system with two inputs U_x and U_y and two outputs x and y ; (b) : simplified representation, with $U = (U_x \quad U_y)^T$ the input voltages vector and $d = (x \quad y)^T$ the tube deflections vector.

identified is composed of four functions $G_{xx}(s)$, G_{yx}, G_{xy} and G_{yy}, which are functions for transfers $U_x \to x$, $U_x \to y$, $U_y \to x$ and $U_y \to y$, respectively. These functions are identified by applying the *ARMAX* method to the individual experimental step responses of Fig. 3 (blue solid line). The obtained transfer functions are represented by Eq. 1. Afterwards, the model $G(s)$ is simulated by using *Matlab/Simulink* and compared to the experimental results. The comparison is established in Fig. 3, where we notice a good agreement between them.

$$G(s) = \begin{pmatrix} G_{xx}(s) & G_{xy}(s) \\ G_{yx}(s) & G_{yy}(s) \end{pmatrix} \quad \text{with} \quad \begin{cases} G_{xx}(s) = \frac{4.4718\times10^{15}(s+319.7)(s^2+570.5s+4.968\times10^7)}{(s+3.625\times10^4)(s+1.207\times10^4)(s+313.9)(s^2+536.5s+3.558\times10^7)} \\ \quad \times\frac{(s^2+873.8s+1.102\times10^8)}{(s^2+1352s+1.025\times10^8)(s^2+469.2s+1.081\times10^8)}\,; \\ G_{yx}(s) = \frac{-10.534(s-1.513\times10^4)(s^2+610.3s+3.342\times10^5)}{(s^2+567s+2.882\times10^5)(s^2+1.208\times10^4s+3.673\times10^7)} \\ \quad \times\frac{(s^2+807.4s+2.329\times10^7)(s^2+57.97s+5.737\times10^7)}{(s^2+1132s+1.82\times10^7)(s^2+516.2s+3.491\times10^7)}\,; \\ G_{xy}(s) = \frac{-3.8154(s+487.2)(s^2+20.85s+2.836\times10^7)}{(s+6337)(s+351.2)(s^2+394.1s+3.605\times10^7)} \\ \quad \times\frac{(s^2+2207s+7.762\times10^7)(s^2-2.826\times10^4s+2.733\times10^9)}{(s^2+517.2s+6.043\times10^7)(s^2+628.3s+2.384\times10^8)}\,; \\ G_{yy}(s) = \frac{-9.0985\times10^5(s-1.871\times10^4)(s^2-98.19s+9.619\times10^7)}{(s+3984)(s^2+6789s+5.067\times10^7)(s^2+321.5s+6.015\times10^7)}. \end{cases} \tag{1}$$

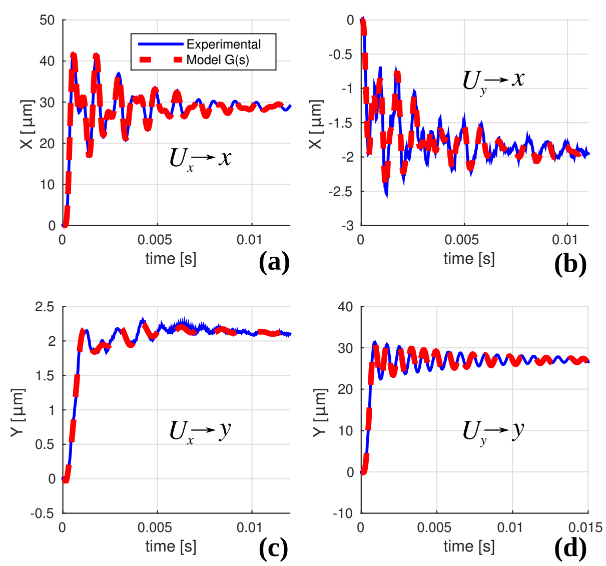


FIGURE 3: Representation and comparison of the characterized vibrations (blue solid line) and the identified model (red dashed line). (a) and (d) : direct transfers ; (b) and (c) : cross-couplings.

4. CALCULATION OF THE H_∞ COMPENSATOR

The compensator is calculated according to the scheme of Fig. 4a, where G is the initial system with input $U = (U_x \quad U_y)^T$ and output $d = (x \quad y)^T$, K is the 2-DoF vibrations compensator to be calculated, and $d_r = (x_r \quad y_r)^T$ the desired (reference) deflection vector. Fig. 4b, represents the augmented system from which the standard H_∞ problem is defined. Weighting functions W_r, W_1 are chosen based on the performances (static error, bandwidth, etc) desired for the compensated system. The weighting W_2 is used to limit the control voltage, in order to avoid the saturation of the actuator.

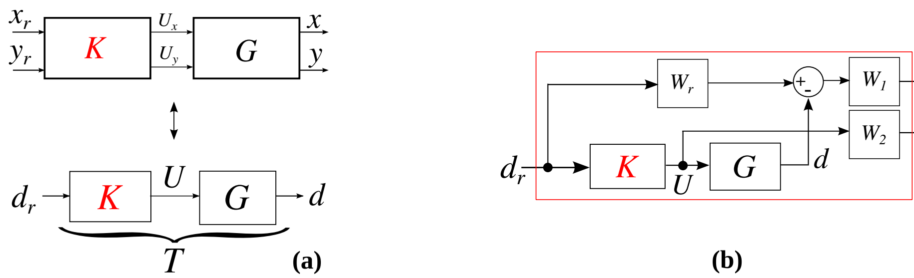


FIGURE 4: Compensation scheme and the structure of the augmented system, from which the H_∞ problem is defined. (a) : initial system G with the compensator K ; (b) : the compensated system augmented with weighting functions W_r, W_1 and W_2.

The chosen weighting functions are represented in Eq. 2 :

$$W_r(s) = \begin{pmatrix} \frac{1}{1+\frac{0.01}{3}s} & 0 \\ 0 & \frac{1}{1+\frac{0.01}{3}s} \end{pmatrix}; W_1(s) = \begin{pmatrix} \frac{s+120}{s+1.2} & 0 \\ 0 & \frac{s+120}{s+1.2} \end{pmatrix}; W_2(s) = \begin{pmatrix} 0.125 & 0 \\ 0 & 0.125 \end{pmatrix}. \quad (2)$$

From the augmented system in Fig. 4b, the transfer between the exogenous input d_r and exogenous outputs z_1 and z_2 is expressed as :

$$\begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = \begin{pmatrix} W_2K \\ W_1W_r - W_1T \end{pmatrix} d_r, \quad (3)$$

with $T = GK$ the transfer function of the compensated system.

The standard H_∞ problem consists therefore in finding the controller K such that :

$$\left\| \begin{matrix} W_2K \\ W_1W_r - W_1T \end{matrix} \right\|_\infty < \gamma \quad \text{or} \quad \begin{cases} \|K\|_\infty < \|W_2^{-1}\|_\infty \gamma \\ \|W_r - T\|_\infty < \|W_1^{-1}\|_\infty \gamma \end{cases}, \quad (4)$$

where γ represents the performances evaluation parameter. We have solved this problem by using DGKF algorithm [11] and a 2-DoF feedforward compensator K, with order 34 and $\gamma = 0.929688$, has been obtained. This compensator was not implementable in real time with the dSPACE-1103 board. We have therefore reduced its order by using the balanced-reduction technique, and a new compensator with order 20, able to run in real time on the aforementioned card, has been obtained.

5. IMPLEMENTATION OF THE COMPENSATOR AND COMPENSATION RESULTS

The aim of this section is to verify the ability of the calculated compensator to suppress the vibrations of direct transfers and to reduce the cross-couplings amplitudes. Before the implementation of the compensator, the simulations of frequency responses for the initial system G (piezoelectric tube), the controller K (with reduced order) and the compensated system T, have been evaluated. These responses are represented in Fig. 5, where

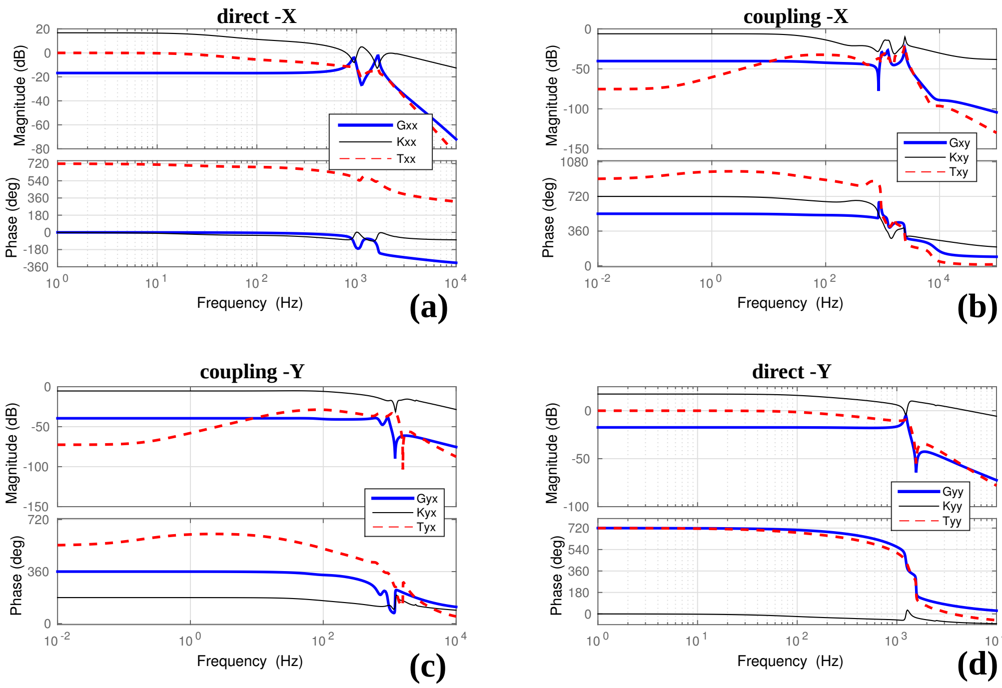


FIGURE 5: Frequency responses of the initial system G, the compensator K and the compensated system T. (a) et (d) : direct transfers ; (b) and (c) : cross-couplings.

we notice a bandwidth of more than 80Hz for direct transfers and the rejection of couplings up to -70dB at low frequencies.

Afterwards, the 2-DoF reduced compensator K has been implemented according to the scheme of Fig. 4a, in *Simulink/Matlab* software. In order to test the suppression of the vibrations and the reduction of the cross-couplings amplitudes, step inputs x_r and y_r of 20μm have been applied successively. The obtained transient responses are reported in Fig. 6. The comparison of results in this latter figure, and results in Fig. 3 (before compensation) shows that, thanks to the calculated compensator, the vibrations in direct transfers are suppressed and the cross-couplings amplitudes are reduced by more than 50%.

6. CONCLUSION AND PERSPECTIVES

Multivariable feedforward control of vibrations based on standard H_∞ approach has been presented in this paper. The technique was applied to a 2-DoF piezoelectric tube scanner. Simulation and experimental results have proven the efficacy of the proposed approach in terms of vibrations suppression, cross-couplings amplitudes reduction and the ease of implementation of the calculated compensator. In future works, additional control techniques will be integrated to the proposed approach, in order to increase the overall bandwidth of the compensated system.

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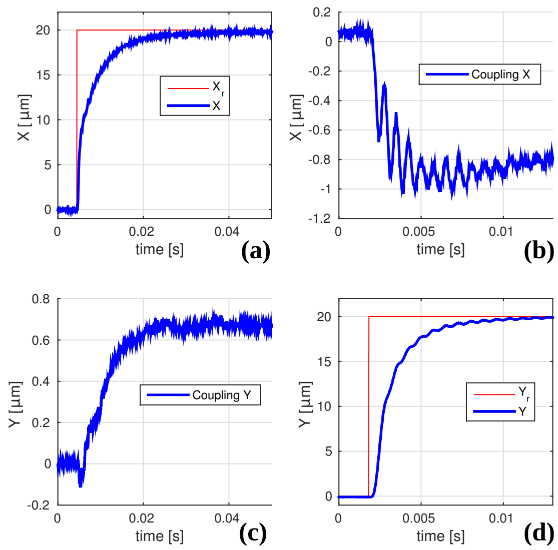

FIGURE 6: Verification of the vibrations and cross-couplings amplitudes for the compensated system. (a) and (d) : direct transfers ; (b) and (c) : cross-couplings.

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