euspen's 17th International Conference & Exhibition, Hannover, DE, May 2017
www.euspen.eu

Control concept to minimize the settling time for a point-to-point motion of a single-axis piezo-actuated nanopositioning system with a displacement amplification mechanism.

Aditya Suryadi Tan[1], Thomas Sattel[1] and Michael Koschig[2]

[1]Technische Universität Ilmenau, Germany and [2]piezosystem Jena GmbH

aditya-suryadi.tan@tu-ilmenau.de

Abstract

Iterative learning control (ILC) is able to overcome the limitation of feedback and conventional feedforward control in producing the suitable control signal for repetitive motion. Therefore, this control method has become attractive in nanopositioning, recently. In this paper, an ILC based control concept for a piezo-actuated nanopositioning system with a displacement amplification mechanism will be introduced. The controller will utilize an A-Type ILC, whose learning bandwidth is proven to be bigger in comparison to other types of ILC. The ILC will be combined together with an inverse based feedback controller and an input shaper, whose combination hasn't been found to be applied in a piezo-actuated nanopositioning system. It was theoretically shown, that this combination is capable to maximize the learning bandwidth and at the same time increase the robustness of the controlled system. Moreover, the control design offers a simplicity advantage, since only a frequency response of the system's plant is needed. For verification purpose, the designed controller was implemented on an industrial piezo-actuated single axis nanopositioning system, in which a displacement amplification is integrated. Investigations will be conducted specifically for a point-to-point motion, since the performance of the controller can be clearly observed through the achieved settling time. The measurements show that the controller is able to deliver the appropriate control signal for this kind of motion task. As a result, the settling time can be minimized, up to the limitations due to nonlinearities, low dominant eigenfrequency and the lightly damped dominant eigenmode. The measurements were also compared with both theoretical results and theoretical achievable settling time for a critically damped system, in which a good agreement were presented.

Keywords: Nanopositioning, iterative learning control, point-to-point motion, settling time and high bandwidth

1. Introduction

Piezo-actuated nanopositioning systems can have a larger displacement by using displacement amplification mechanisms. On the contrary, such mechanisms extremely reduce the eigenfrequencies. The problem exists when eigenfrequencies lie in the excitation frequency spectrums of a point-to-point motion. Therefore, controller with large operating bandwidth is demanded.

An inverse based feedback controller [1] allows an easy control design and work indirectly as a bandpass filter for the reference signal. Even though the end point of a point-to-point motion can be perfectly achieved, this filtering may cause an unsmooth trajectory and longer time in its transition. By a repetitive positioning task, an improvement can be made by using an iterative learning control (ILC). Anticipatory (A)-Type ILC that offers the largest operating bandwidth in compare to the other types of ILC is in [2] introduced. Similar approach is used in [3], where the anticipatory concept is used in a model based ILC and combined with a Gaussian filter and feedback controller to perform a triangle wave motion.

In this paper, a control concept to improve the performance of the above mentioned system for a point-to-point motion will be introduced. It is a combination of an A-Type ILC and an inverse based feedback controller, whose characteristics are able to complement each other weakness. The feedback controller is in charge to give a starting signal for the ILC's learning process, which covers mostly the frequency spectrums that are lower than the resonance frequency. The ILC will be responsible to reduce the remaining error, which are caused by the rest of the required frequency spectrums and phase delay of the feedback controller. Additionally, an input shaper will be added to make sure that the frequency spectrums of the reference signal are inside of the controller's operating bandwidth. The proposed control concept offers a high performance and a simple design process advantages.

The controller is implemented and tested in a piezo-actuated nanopositioning system with two different operating conditions. The performance of the point-to-point motion will be characterized by its settling time and an ideal critically damped system will be used as the performance benchmark. This paper will explain how to design the controller and verify the results through experiments.

2. Control Design

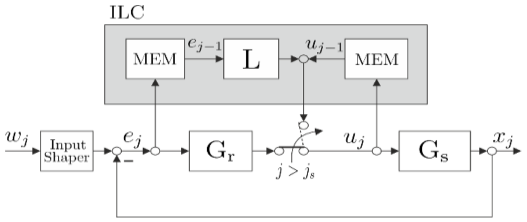

Figure 1. Signal flow diagram of the proposed controller

Figure 1 shows the signal flow diagram of the proposed controller, where *w* is the reference signal, *e* is the error, *u* is the control signal, *x* is the measured position, and *j* is the cycle index. The inverse based feedback controller will be used only to give a start for the learning process and will be switched off after the hysteresis is compensated for one full cycle (j_s). After the switching, only the ILC will operate to shape the control signal until the appropriate signal is generated, whereby the desired result can be achieved.

2.1. System's plant

The system's plant will be an X-Axis Positioning Stage PX200 from piezosystem jena GmbH together with its amplifier and position sensor. It will be identified by measuring the frequency response and modelled by a transfer function that consist of a PT_2- in series with a time delay function:

$$G_s(s) = \frac{K\,{\omega_0}^2}{s^2 + 2\,\xi\omega_0\,s + \,{\omega_0}^2}\;e^{-T_z\,s}, \tag{1}$$

where ξ is a damping factor, ω_0 is the resonance frequency, K is the plant's gain and T_z is the time delay.

2.2. Inverse based feedback controller

The inverse based controller will take the form of a $PIDT_1$ controller with its transfer function and close loop transfer function as follow:

$$G_r(s) = \gamma\,.\frac{\left(K_d + \,K_pT_n\right)s^2 + \,\left(K_p + \,K_iT_n\right)s + \,K_i}{(\,T_n\,s + 1)\,s}, \tag{2}$$

$$G_{cl}(s) = \frac{\gamma}{T_n\,s^2 + s + (\gamma^{-1})}, \tag{3}$$

where K_p, K_i, K_d, and T_n are the $PIDT_1$ parameters and γ is an amplification factor. These $PIDT_1$ parameters can be obtained by compensating the denominator of the PT_2 function in equation (1) with the controller's numerator in equation (2). Critically damped close-loop system (ξ = 1) can be achieved by setting the gain to have a ratio of $\gamma.T_n = 0.25$.

2.3. A-Type iterative learning control

A-Type ILC's learning function and convergence condition are

$$L(s) = \beta\;e^{(d\,s)}, \tag{4}$$

$$G_{conv}(s) = |\,1 - L(s)\;G_s(s)\,| < 1. \tag{5}$$

with β as the learning gain and d as a time shifting unit that influence the operating bandwidth and learning rate of the ILC. This bandwidth can be analysed through equation (5) and is defined as the first frequency for $G_{conv}(j\omega)$ to have a magnitude bigger than one. Figure 2 shows the transfer function of equation (3) and equation (5) in one bode plot.

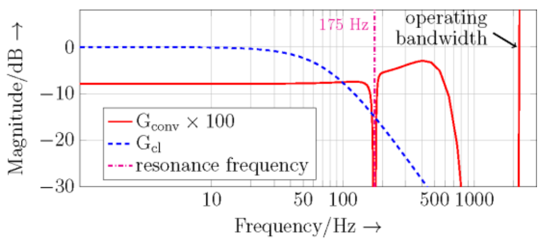

Figure 2. Magnitudes bode plot for the close loop transfer function with feedback controller and the convergence function for A-Type ILC for operating load of 0 g with resonance frequency of 175 Hz.

For the close loop transfer function, 0 dB gain means that the output exactly equal to the input. It can be seen from the blue line that the feedback controller able to eliminate the error of the low frequency spectrums up to around 30 Hz. In contrary, in the area where the high frequency spectrum is filtered by the controller, ILC works better up to its operating bandwidth. It is shown through its learning rate that is described by the green line. The lower it is from the 0 dB line, the faster is the learning rate. In this way, the ILC will compensate indirectly the inversion inaccuracy of the feedback controller.

3. Aimed settling time for point-to-point motion

Through the integrated amplification mechanism, the first resonance frequency of the piezo nanopositioning system is reduced from 76 kHz to 175 Hz. With an additional mass of 50 g, the resonance frequency is reduced even further to 135 Hz. The proposed controller will be aimed to achieve a settling time of a 40 µm displacement that could be achieved in an ideal critically damped condition (ξ = 1). By analysing equation (1) numerically, the theoretical achievable settling time can be obtained, which resulting in 9.2 ms and 12.7 ms respectively for operating load of 0 g and 50 g. The reference signal will be shaped so that the transition time is the aimed settling time and there is no step changes up to its highest dynamic order.

4. Experimental results

The measurement results of the controlled point-to-point motion for both operating conditions are depicted in figure 3. It is shown that suitable control signal is able to be generated, so that the measured position follows exactly the reference signal and arrives in the desired position within the defined settling time, which is 9 ms for 0 g operating load and 12 ms for 50 g operating load.

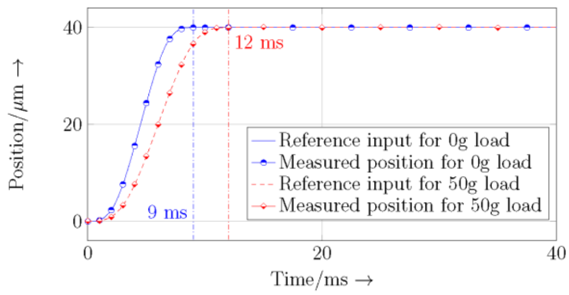

Figure 3. Experimental results for a controlled point-to-point motion for operating load of 0 g and 50 g.

5. Conclusion

The proposed controller is tested in a piezo actuated nanopositioning system under two different working conditions. It can be seen through the results that the targeted settling time for each condition was achieved. It can be concluded that the proposed controller has enough operating bandwidth and is able to improve the performance of such system for a point-to-point motion up to the aimed settling time. For future works, investigations need to be conducted to find out how far the performance can be improved even further and how to guarantee the learning convergence for all operating conditions.

References

[1] Janschek K 2012 Mechatronic System Design. „Heidelberg, Berlin: Springer", 667

[2] Wang D 2005 Design and Experiments of an Anticipatory Learning Control: Frequency-Domain Approach *IEEE/ASME Transactions on Mechatronics* **10(3)** 305-313

[3] Bristow D, Dong J, Alleyne A G, Ferreira P, Salapaka S 2008 High bandwidth control of precision motion instrumentation *Review of Scientific Instruments* **79** 103704-1 – 103704-14