Similarity-based Feedback Control with Reduced Capacitive Load for Linear Operation of Piezoelectric Actuators

Mathias Poik Dominik Kohl Georg Schitter

Automation and Control Institute (ACIN), TU Wien, Gusshausstrasse 27-29, 1040 Vienna, Austria. Email: poik@acin.tuwien.ac.at

Abstract: This paper presents a hysteresis compensating control scheme that uses two piezoelectric transducers with similar hysteretic behavior. The transducers are supplied with the same voltage and the measured displacement of one of them is used to operate the other one in "open-loop", thereby reducing the hysteresis for a triangular reference signal with a frequency of 1 Hz from 17.5 % to 1.5 %. In order to avoid a significant increase of the capacitive load of the piezo amplifier, two transducers of the same material but different sizes are used, which reduces the required current by 47 % while maintaining the reduced hysteresis of the positioning system.

Keywords: Actuators, Hysteresis, Positioning accuracy

1. INTRODUCTION

Piezoelectric transducers (piezos) are characterized by a high bandwidth, small size and sub-nanometer resolution. They are therefore employed in a variety of high-precision positioning systems, such as Atomic Force Microscopy (AFM) [Binnig and Quate (1986)], laser machining [Park et al. (2012)] and deformable mirrors for adaptive optics [Kanno et al. (2007)]. However, the voltage-displacement relation of piezos shows a distinct hysteresis, which can lead to positioning errors of up to 20 % of their actuation range [Damjanovic (2006)].

A common approach to compensate for the hysteresis is feedforward control using inverse models [Song et al. (2005); Gu et al. (2016)]. In this case, no position sensor is required and a high positioning bandwidth is possible due to the open-loop control structure [Croft et al. (2000)]. However, in order to achieve a good accuracy, complex and computationally expensive models are needed. Additionally, positioning errors due to unavoidable model uncertainties can not be compensated [Zhao and Jayasuriya (1995)]. The majority of the hysteresis appears between applied voltage and resulting charge, and the relation between charge and displacement is roughly linear [Comstock and West (1981)]. Charge control can therefore be used to significantly reduce the hysteresis without a position sensor [Newcomb and Flinn (1982)]. However, leakage currents in the piezoelectric material limit its applicability at low frequencies [Fleming and Moheimani (2004)]. It has been shown that this problem can be circumvented by sensor fusion [Fleming et al. (2008)]. However, this again requires an additional sensor. Additionally, the remaining hysteresis between charge and displacement typically limits the positioning accuracy to 1 %-2 % of the actuation range [Kohl et al. (2017)]. When a position sensor is used, the displacement of the piezo can be measured and controlled [Schitter et al. (2001); Salapaka et al. (2002)]. The resulting positioning accuracy is limited only by the performance of the employed sensor. The most commonly used sensors in nanopositioning applications are capacitive and inductive sensors, as they achieve high bandwidth and accuracy, as well as nanometer resolution [Fleming (2013)]. Laser interferometers are commonly used in metrological systems [Merry et al. (2009)], due to their high absolute accuracy and nanometer resolution over a wide range. However, the integration of such sensors significantly increases the complexity and cost of the positioning system [Fleming (2010)]. In many piezo-based positioning systems the integration of such sensors is therefore undesired or impossible. In deformable mirrors, which can contain hundreds or thousands of actuators, integrating the same number of sensors is often not feasible [Wlodarczyk et al. (2014)]. AFM scanners are desired to be rigid and compact in order to avoid the excitation of undesired resonances [Kindt et al. (2004); Kuiper and Schitter (2010)]. Thus, it is difficult to integrate co-located sensors for feedback control in these applications.

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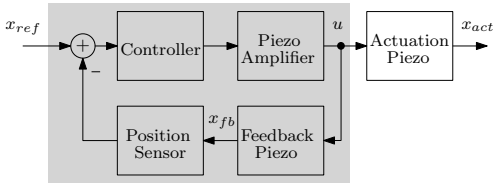

Fig. 1. Block diagram of similarity-based feedback control. The Actuation Piezo is operated without position sensor.

It has been shown that this problem can be circumvented by using similarity-based feedback control [Poik et al. (2018)]. As shown in Fig. 1, two piezos of the same type with similar hysteretic behavior are operated with the same voltage. The Actuation Piezo which performs the positioning task is operated in open-loop. The Feedback Piezo is mounted externally and can therefore easily be measured by a sensor and used for feedback control. The voltage u is thereby adjusted by the controller, such that the displacement x_{fb} follows the reference displacement x_{ref}. Since the two piezos have a similar hysteretic behavior, the displacement x_{act} of the Actuation Piezo is similar to x_{fb}. The piezo performing the positioning task

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is therefore operated linearly without direct position measurement. A drawback of driving the second piezo of the same type with the same voltage is that the capacitive load for the used piezo amplifier is doubled. This is a problem especially for positioning systems with large stack piezos which have a high capacitance. Since the capacitance of the piezos is directly proportional to the required current, the increased capacitive load can significantly increase the complexity and cost of the required piezo amplifier.

To enable hysteresis compensation without significantly increasing the capacitive load, this paper proposes similarity -based feedback control using a second piezo with reduced size and capacitance. A prerequisite for the effectiveness of the control strategy is the relative similarity of the piezos' hysteresis. Therefore, the hysteresis of stack piezos of the same material but different dimensions are analyzed and compared prior to the implementation.

The rest of the paper is organized as follows. Section 2 describes the similarity-based feedback control method and the piezos used for the implementation. In Section 3, the hysteresis of the used piezos is analyzed and compared. The experimental implementation and the results are presented in Section 4. Section 5 concludes the paper.

2. SYSTEM DESCRIPTION

To circumvent the problem of incorporating a co-located sensor into a positioning system, similarity-based feedback control [Poik et al. (2018)] can be used (Fig. 1). The Actuation Piezo which performs the positioning task and the second identical Feedback Piezo are operated with the same voltage u. The displacement x_{fb} of the Feedback Piezo is measured and used for feedback control. The Actuation Piezo is therefore operated linearly without direct position measurement. A disadvantage of this approach is that the capacitive load of the piezo amplifier is doubled, since two identical piezos have to be driven by the amplifier.

In this work, similarity-based feedback control is implemented using a Feedback Piezo of the same material, but with reduced size and therefore reduced capacitance. The positioning accuracy is compared to the previous implementation with an identical Feedback Piezo. The analysis and compensation of nonlinearities is thereby restricted to frequencies below 100 Hz. The influence of the system dynamics is not investigated. The restriction to this frequency range is valid for many piezo-based scanning systems, such as AFM scanners, as the line scan rate is usually well below 100 Hz. It is also valid for many applications of deformable mirrors in adaptive optics (e.g. wavefront correction in telescopes [Madec (2012)] or medical applications [Zawadzki et al. (2005)]).

2.1 Used actuators

Fig. 2 illustrates the piezos used in this work with the experimental setup for comparing their hysteresis. The Actuation Piezo is of the type NAC2013-H08 (Noliac, Kvistgaard, Denmark). It has a length and cross-section of 8 mm and 5 mm × 5 mm, respectively, and a capacitance of 540 nF. Feedback Piezo 1 is identical to the Actuation Piezo. Feedback Piezo 2 is of the type NAC2011-H04 (Noliac, Kvistgaard, Denmark). It has a length and cross-section of 4 mm and 2 mm × 2 mm, respectively. Its capacitance is only 20 nF. All piezos have a maximum voltage of $U_{max} = 150\,\mathrm{V}$. When Feedback Piezo 1 is used for the implementation of similarity-based feedback control, the capacitive load of the piezo amplifier doubles. With Feedback Piezo 2, the capacitive load increases by only 3.7 %.

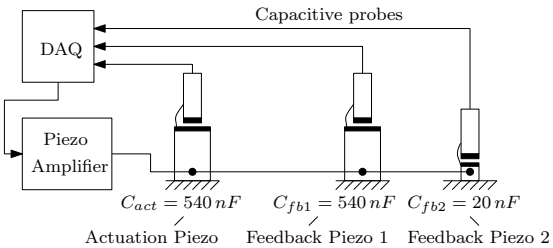

Fig. 2. Experimental setup for the comparison of piezos of the same material and different dimensions.

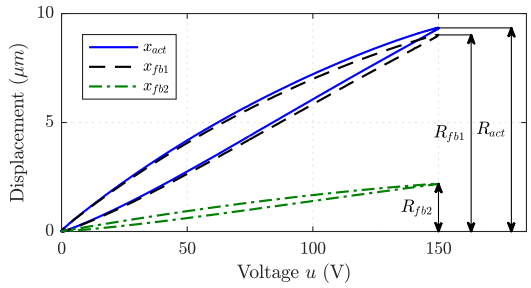

Fig. 3. Actuation ranges of Actuation Piezo and the two Feedback Piezos.

For the comparison of the piezos, different signals are generated by a data acquisition unit DAQ (NI-USB6211, National Instruments, Austin, USA). The piezos are driven by a high-bandwidth low-noise piezo amplifier (TechProject, Vienna, Austria). The displacement of the piezos is measured by capacitive distance sensors (Model-6810, MicroSense, Massachusetts, USA).

2.2 Actuation range

The used piezos have different sizes and therefore also different actuation ranges. For similarity-based feedback control, this would lead to a positioning error and has to be compensated (see Sec. 4).

Fig. 3 shows the displacements x_{act}, x_{fb1} and x_{fb2} of Actuation Piezo, Feedback Piezo 1 and Feedback Piezo 2, respectively, for a sinusoidal voltage with an amplitude of $U_{max}/2$, and a frequency of 10 Hz. The measured actuation ranges of the piezos, defined by the peak-peak value of their displacements, are $R_{act} = 9.34\,\mu\mathrm{m}$, $R_{fb1} = 9.02\,\mu\mathrm{m}$ and $R_{fb2} = 2.19\,\mu\mathrm{m}$. For a comparison of the relative hysteresis, the displacements of the piezos are normalized by their actuation ranges:

$$\bar{x}_{act} = \frac{x_{act}}{R_{act}}, \quad \bar{x}_{fb1} = \frac{x_{fb1}}{R_{fb1}}, \quad \bar{x}_{fb2} = \frac{x_{fb2}}{R_{fb2}}. \tag{1}$$

$\bar{x}_{act}$, $\bar{x}_{fb1}$ and $\bar{x}_{fb2}$ are the normalized displacements of Actuation Piezo, Feedback Piezo 1 and Feedback Piezo 2, respectively.

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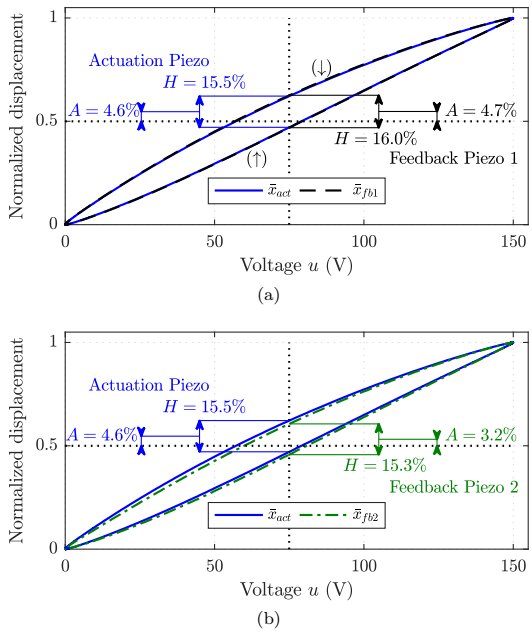

Fig. 4. Comparison of hysteresis and asymmetry between (a) Actuation Piezo and the identical Feedback Piezo 1 and (b) Actuation Piezo and the smaller Feedback Piezo 2.

3. COMPARISON OF NONLINEARITIES

The hysteretic behavior of piezos significantly depends on the amplitude and frequency of the applied voltage [Al Janaideh et al. (2011)]. Therefore, the displacement of the used piezos is analyzed and compared for sinusoidal signals of different amplitudes and frequencies.

The normalized displacements for a sinusoidal voltage with an amplitude of $U_{max}/2$ and a frequency of 10 Hz is shown in Fig. 4. The hysteresis curves are quantified using the same parameters as in [Poik et al. (2018)]. Hysteresis H is defined as difference between the two branches (ascending (↓) and descending (↓))

$$H = \bar{x}\left(\frac{U_{max}}{2}\downarrow\right) - \bar{x}\left(\frac{U_{max}}{2}\uparrow\right). \tag{2}$$

The difference of the center of the hysteresis curves from 0.5 is denoted as Asymmetry A

$$A = \frac{\bar{x}\left(\frac{U_{max}}{2}\downarrow\right) + \bar{x}\left(\frac{U_{max}}{2}\uparrow\right)}{2} - 0.5\,. \tag{3}$$

Both parameters are defined at a voltage of $u = U_{max}/2$.

In Fig. 4a, the hysteresis curves of Actuation Piezo and the identical Feedback Piezo 1 are compared. It can be seen the the parameters quantifying the hysteresis curves are similar. Hysteresis and Asymmetry show a difference of only 0.5 % and 0.1 % of the actuation range R_{act}, respectively. As shown in Fig. 4b, Hysteresis and Asymmetry of Actuation Piezo and the smaller Feedback Piezo 2 differ by 0.2 % and 1.3 %, respectively.

Fig. 5 shows Hysteresis and Asymmetry of the used piezos for different amplitudes of the applied sinusoidal voltage.

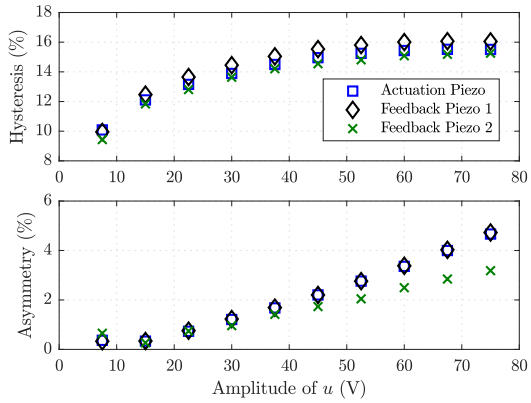

Fig. 5. Hysteresis and asymmetry of Actuation Piezo and Feedback Piezos depending on the amplitude of the applied voltage.

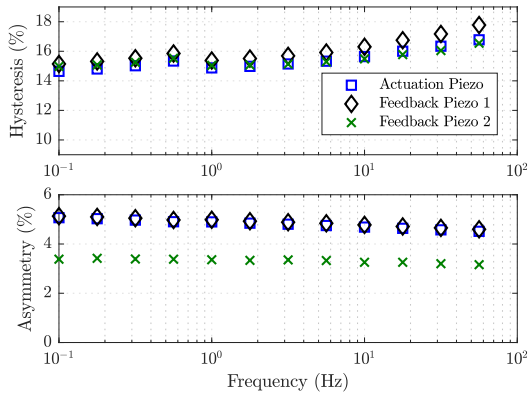

Fig. 6. Hysteresis and asymmetry of Actuation Piezo and Feedback Piezos depending on the frequency of the applied voltage.

Offset and frequency of the voltage are kept constant at $u = U_{max}/2$ and 10 Hz, respectively. For all piezos, both parameters increase with increasing amplitude. However, Hysteresis of Actuation Piezo and either of the Feedback Piezos differ by only up to 0.6 % of R_{act}, independent of the amplitude of the applied voltage. Asymmetry of Feedback Piezo 2 shows a maximum difference of 1.5 % for larger amplitudes of the applied voltage.

To investigate the frequency dependence of the hysteresis curves of the piezos, a sinusoidal frequency sweep with a constant amplitude of $U_{max}/2$ and an offset of $U_{max}/2$ is applied. Fig. 6 shows Hysteresis and Asymmetry depending on the frequency of the applied voltage. It can be seen that the hysteresis curves of the compared piezos show a similar frequency dependence. The difference of Hysteresis between Actuation Piezo and either of the Feedback Piezos equals 0.5 % to 1 % of R_{act}. Asymmetry of Actuation Piezo and Feedback Piezo 1 is almost identical for the entire frequency range. The difference of Asymmetry of Actuation Piezo and Feedback Piezo 2 varies from 1.7 % at low frequencies to 1.3 % at higher frequencies.

In summary, the compared hysteresis curves of Actuation Piezo and Feedback Piezo 1 are similar and differ by

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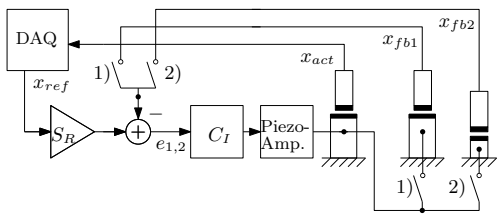

Fig. 7. Experimental implementation of similarity-based control using 1) Feedback Piezo 1 and 2) Feedback Piezo 2.

only up to 1 % of the actuation range, which is in accordance with the results presented in [Poik et al. (2018)]. The Actuation Piezo has a maximum Hysteresis and Asymmetry of 17.9 % and 5.1 %, respectively. Although the Actuation Piezo has an actuation range that is more than 4 times larger than Feedback Piezo 2, their hysteresis curves show a relative difference of only up to 1.7 %. It is therefore expected that the hysteresis of the Actuation Piezo can be significantly reduced by using the measured displacement of Feedback Piezo 2 for feedback control.

4. IMPLEMENTATION AND EXPERIMENTS

4.1 Implementation

The positioning accuracy of the Actation Piezo with similarity-based feedback control is evaluated using 1) Feedback Piezo 1 and 2) Feedback Piezo 2. The experimental implementation of the control strategies can be seen in Fig. 7 by closing the switches 1) or 2), respectively. As mentioned in Section 2, the actuation ranges of the piezos show significant differences. This difference is compensated by multiplying x_{ref} with the scaling factor S_R. For the implementation of 1) and 2), the difference between the actuation ranges is compensated by $S_R = R_{fb1}/R_{act}$ and $S_R = R_{fb2}/R_{act}$, respectively. The tracking error $e_{1,2} = x_{ref}S_R - x_{fb1,2}$ is applied to a custom-made analog integral controller C_I. For the implementation of 1), the controller gain is manually adjusted by the following procedure [Kohl et al. (2016)]: The gain is increased until ringing occurs and then reduced by 10 %, with a resulting closed-loop bandwidth of 615 Hz (data not shown). For the implementation of 2), the gain is tuned such that the same closed-loop bandwidth is achieved.

The noise level of the displacement x_{act} of the Actuation Piezo is dominated by the noise of the position sensor in the feedback path. Since Feedback Piezo 2 has a reduced length and actuation range, the signal to noise ratio is reduced when Feedback Piezo 2 is used. A possibility to overcome this drawback would be the use of a Feedback Piezo with increased length and reduced cross-section, which leads to a higher actuation range while maintaining a low capacitance.

In a practical application of the proposed method, a mechanical load would be attached to the Actuation Piezo, while the Feedback Piezo remains unloaded. During actuation the load exerts a counter-force on the Actuation Piezo. However, in many nanopositioning applications the mass of the positioned objects is small and the influence of the counter-force on the nonlinear behavior can be neglected [Rakotondrabe (2011)].

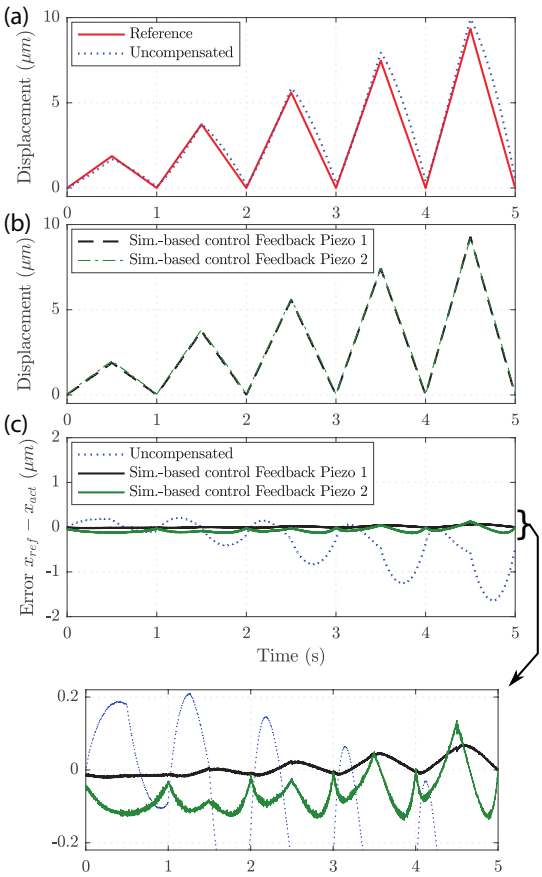

Fig. 8. Displacement of Actuation Piezo for triangular trajectory (a) without compensation and (b) with compensation by similarity-based feedback control. (c) Comparison of positioning errors with and without compensation.

4.2 Experimental Verification

In most piezo-based scanning systems, triangular scan trajectories are used. The positioning accuracy is therefore evaluated for a ramped triangular reference signal x_{ref}, which is shown in Fig. 8a. Additionally, the measured displacement x_{act} of the Actuation Piezo without compensation for hysteresis is plotted, which shows a large positioning error of 1.64 μm, which equals 17.5 % of R_{act} (Fig. 8c). In Fig. 8b, x_{act} is shown for similarity-based feedback control. The corresponding positioning error $x_{ref} - x_{act}$ is shown in Fig. 8c. When the identical Feedback Piezo 1 is used for feedback control, the maximum positioning error equals 71 nm (0.8 %). In order to reduce the capacitive load of the piezo amplifier the smaller Feedback Piezo 2 can be used, which shows a maximum error of 139 nm (1.5 %). The positioning errors can be explained by the differences of the nonlinearities of the individual piezos, as analyzed in the previous section.

As shown in Fig. 8c, without compensation for hysteresis the displacement shows a significant drift. This can be explained by creep due to the increasing offset of the trian-

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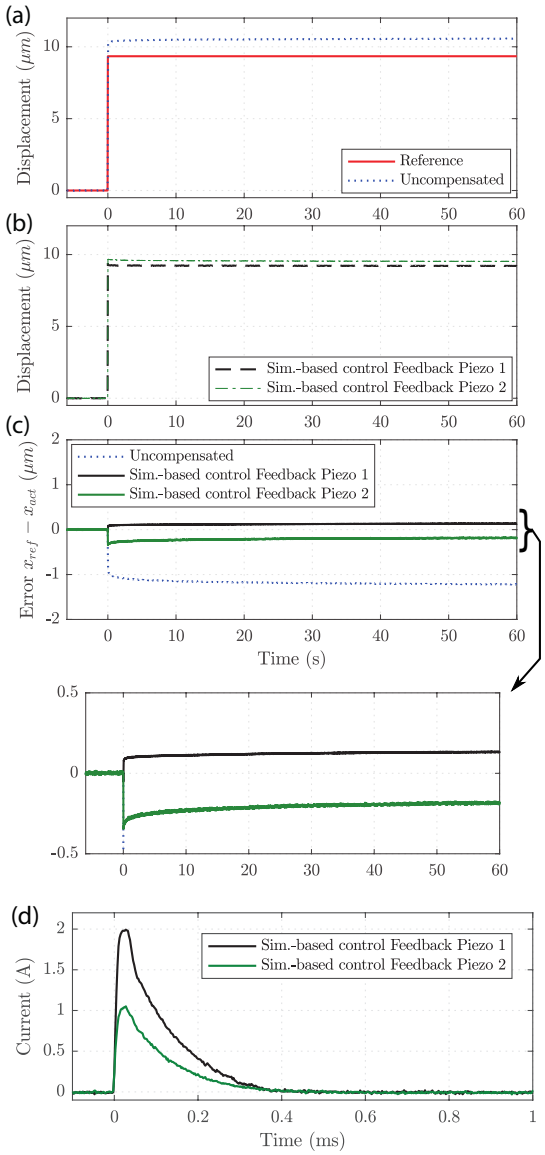

Fig. 9. Displacement of Actuation Piezo for step trajectory (a) without compensation and (b) with compensation by similarity-based feedback control. (c) Comparison of positioning errors with and without compensation. (d) Amplifier output current (note the different time scale).

gular reference signal. With compensation, no significant drift is observed, which indicates that the creep behavior of the used piezos is similar and can also be compensated by similarity-based feedback control. To investigate the slow drift due to creep, a step of the reference signal with a step height of R_{act} is applied and the displacement is recorded for 60 s. A similar analysis was carried out in [Poik et al. (2018)]. This is shown in Fig. 9a, along with the displacement without compensation. As shown in Fig. 9c, the displacement shows a large positioning error of 1.22 μm, which equals 13.1 % of R_{act}. The displacement with similarity-based control is shown in Fig. 9b, and the resulting positioning errors are compared in Fig. 9c. When Feedback Piezo 1 is used, the maximum error equals 136 nm (1.5 %). Since the displacement of Feedback Piezo 1 is used for feedback control, the positive error indicates that Feedback Piezo 1 has a larger step height than the Actuation Piezo. However, the error varies by only 0.5 % within 60 s, which shows that the slow drift due to creep is similar. With Feedback Piezo 2, the displacement shows an initial negative error of 346 nm (3.7 %), indicating that Feedback Piezo 2 has a smaller step height than the Actuation Piezo. The error reduces to 2 % after 60 s, which shows that the drift of the two piezos due to creep differs by 1.7 %. With respect to the uncompensated case, the maximum positioning error is reduced by 71 %.

To demonstrate the benefit of using a piezo with reduced capacitance, the output current of the piezo amplifier is compared for the two implementations of similarity-based feedback control. It is measured by a 1147B current probe and acquired by a DSO-X 4024A Oscilloscope (Keysight Technologies, Santa Rosa, USA). As shown in Fig. 9d, the required maximum current for similarity-based control with Feedback Piezo 1 equals 2 A. When Feedback Piezo 2 is used, the current is reduced by 47 %, which is in accordance with the reduction of the capacitive load due to the reduced size of the piezo.

In summary, it has been shown that the similarity of two piezos of the same material but different dimensions can be used to operate one of them in open-loop with reduced hysteresis, without a significant increase of the capacitive load.

5. CONCLUSIONS

The presented control strategy reduces the hysteresis of a stack piezo without the need of a co-located position sensor by using two piezos of the same material and different dimensions. While the used piezos show a hysteresis of up to 17.9 % of the actuation range, the hysteresis curves of the individual piezos differ by only about 1.7 %. This similarity is employed to operate one of the piezos without direct position measurement, thereby reducing the positioning error for a triangular reference signal from 17.5 % to 1.5 %. Since the error is caused by the difference between the piezos, it is expected that it can be further reduced using piezos with matched hysteretic behavior (e.g. by using piezos from the same batch). To reduce the capacitive load, a piezo with smaller size and capacitance is used for feedback control, thereby reducing the output current of the piezo amplifier by 47 % with respect to the previous implementation of similarity-based feedback control.

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