A NOVEL APPROACH FOR REDUCING THE SETTLING TIME OF ROLLER BEARING NANOPOSITIONING STAGES USING HIGH FREQUENCY VIBRATION

Xin Dong, Xiaowen Zhang, Chinedum E. Okwudire
Mechatronics and Sustainability Research Lab
Department of Mechanical Engineering, University of Michigan
Ann Arbor, MI, USA

OVERVIEW

This paper presents vibration assisted nanopositioning (VAN) – a novel approach for mitigating the adverse effects of pre-rolling friction on the settling time of roller bearing nanopositioning stages using high frequency vibration. The novelty of VAN is in the way it synergistically combines the mechanical design and control of the stage to mitigate pre-rolling friction without jeopardizing positioning precision. After a brief introduction, the concept of VAN is described and its superior performance and robustness relative to a recently-proposed friction compensation method is demonstrated in simulations. The design of a prototype VAN stage is then outlined, and the prototype stage is used in preliminary experiments to demonstrate up to 61.7% reduction of settling time compared to a stage without VAN.

BACKGROUND AND MOTIVATION

Nanopositioning (NP) stages are used for precise positioning in a wide range of ultra-precision processes, ranging from MEMS inspection to micro additive manufacturing. They can be constructed using flexure, fluidic, magnetic or roller bearings. Flexure-based stages are compact, low-cost and friction free. However, their limited stroke and load capacity make them unsuitable for large-range, medium-to-high-payload applications e.g., nanoimprint lithography [1]. Magnetic bearings are capable of large range nanopositioning but their commercial use is currently relegated to the highest end stages (such as those used in semiconductor manufacturing [2]) because of their high costs and complexities. Fluidic (i.e., hydrostatic or aerostatic) bearings are also capable of large-range nanopositioning but they are not suitable for clean room and/or high vacuum environments.

Roller bearing NP (RB-NP) (i.e., crossed roller and linear ball bearing) stages are the most cost effective type of NP stages. Moreover, they are currently the only commercially viable option for a growing number of large-range NP applications that must be performed in high or ultra-high vacuum environments, e.g., scanning electron microscopy [3] and focused ion beam [4]. However, the presence of friction adversely affects their performance. A typical RB-NP stage takes a very long time to reach its target position in point-to-point positioning due to the so-called "pre-rolling friction," which dominates as the stage gets within microns of its target position [5]. Such long settling times severely hamper the throughput of the processes for which RB-NP stages are used.

The state of art in addressing friction in RB-NP stages is to perform model-based friction compensation through feed forward or feedback controllers [6]. Friction compensation works well if the friction model is sufficiently accurate [6]. However, due to the extreme variability of friction dynamics, particularly in the pre-rolling regime, such methods typically suffer from poor robustness. Several methods have been proposed in the literature for improving the robustness of friction compensation, mainly through model parameter adaptation [6, 7]. However, the convergence of adaptation schemes is often difficult and slow because the identification signals are not rich (or persistent) enough [6]. Another approach is to use a feedback controller with very good rejection of un-modeled or poorly modeled disturbances [6]. The result is often a high gain or nonlinear controller which could lead to instability or undesirable limit cycles.

Dither is well-known to be an effective and robust way of mitigating nonlinear phenomena like friction, backlash and hysteresis [8]. For dither to work effectively, the frequency and amplitude of oscillations must be high [8]. Therefore, when considering dither for friction mitigation in RB-NP stages, the following problems emerge:

- Traditionally, the dithering force (F_d) is applied indirectly to the location of friction (F_f) by adding it to the servo actuation force (F_a) of the stage (see Figure 1(a)). However, the effectiveness of dither is greatly attenuated by the low-pass filtering effect resulting from the stage dynamics.
- Applying high amplitude dither to a precise positioning stage through its servo actuator causes excessive vibration of the stage thus jeopardizing its positioning performance; there is no guarantee that the stage will stop at the desired position after dither is turned off.
- When high amplitude dither is maintained for prolonged periods of time, it causes accelerated wear of mechanical components and excessive heat generation.

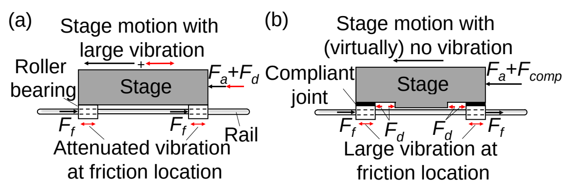

FIGURE 1 Schematic representation of (a) traditional approach; and (b) proposed VAN approach of applying dither to a positioning stage.

VIBRATION ASSISTED NANOPOSITIONING

Concept

To address the limitations of traditional dithering, we propose a novel approach of applying dither to RB-NP stages which we call vibration assisted nanopositioning (VAN). As shown in Figure 1(b), it comprises the following features:

- Each roller bearing is not rigidly attached to the stage; rather it is attached using a joint that is complaint in the stage's direction of motion but stiff in other directions.
- F_d is applied directly to each roller bearing using a small actuator (e.g., voice coil or piezo stack) to create large enough vibration amplitudes at the location of friction.
- F_d is applied with a phase difference of 180° to the bearings on opposite ends of the stage such that the reaction forces transmitted to the stage (mostly) cancel out.
- The adverse effects of un-cancelled vibration, heat and wear are minimized by regulating the applied dither force and/or by applying a compensating force (F_{comp}) through the actuator of the stage.

Simple Model of VAN Stage

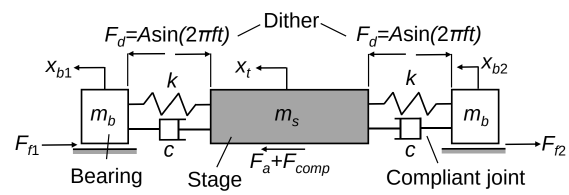

FIGURE 2 Simple model of VAN stage.

Figure 2 shows a simple three-mass model of a closed-loop controlled VAN stage. The compliant joint connecting the stage of mass m_s to each bearing of mass m_b is modeled by spring stiffness k and damping coefficient c. Dither is applied in the form of a harmonic excitation force F_d, with amplitude A and frequency f. The system dynamics are described by

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{F}, \tag{1}$$

where **M**, **C** and **K** are respectively the mass, damping and stiffness matrices, while **u** and **F** are respectively the displacement and force vectors of the system. They are given by

$$\mathbf{M} = \begin{bmatrix} m_b & 0 & 0 \\ 0 & m_b & 0 \\ 0 & 0 & m_s \end{bmatrix}, \mathbf{C} = \begin{bmatrix} c & 0 & -c \\ 0 & c & -c \\ -c & -c & 2c \end{bmatrix},$$
$$\mathbf{K} = \begin{bmatrix} k & 0 & -k \\ 0 & k & -k \\ -k & -k & 2k \end{bmatrix}, \mathbf{F} = \begin{Bmatrix} F_d - F_{f1} \\ -F_d - F_{f2} \\ F_a \end{Bmatrix}, \mathbf{u} = \begin{Bmatrix} x_{b1} \\ x_{b2} \\ x_s \end{Bmatrix}, \tag{2}$$

where x_b and x_s are respectively the displacements of stage and bearings. The subscripts 1 and 2 attached to F_f and x_b are used to distinguish between the displacements and friction forces of each bearing, which may be different.

SIMULATION BASED ANALYSIS OF VAN

VAN is evaluated in simulations by comparing its settling performance with that of the Nonlinear Integral Action Settling Algorithm (or NIASA for short) proposed by Bucci et al. [9]. In [9], a PID controlled Aerotech ALS-130H RB-NP stage with total moving mass m = 1.5 kg is used to evaluate NIASA in simulations. Its P and D gains are respectively 0.8 N/μm and 8.5 × 10^{-4} N·s/μm, but its integral gain is a nonlinear function of the friction force F_f, assumed to be described by the Dahl model [10], given by

$$\frac{dF_f}{dx_r} = \sigma\left(1 - \frac{F_f}{F_c}\operatorname{sgn}\dot{x}_r\right)^i, \tag{3}$$

where x_r is the relative displacement between the sliding surfaces, σ = 8 N/μm is the initial stiffness, F_c = 1 N is a measure of the Coulomb friction force and i = 1 is a shape factor.

To compare with NIASA, a PID controlled VAN stage is modeled as shown in Figure 2, with m_s = 1 kg, m_b = 0.25 kg, k = 5 N/μm, c = 2 × 10^{-5} N·s/μm (corresponding to 1% damping ratio) and $F_{f1} = F_{f2} = F_f$. Note that the total mass of the VAN stage (i.e., $m = m_s + 2m_b$), its P and D controller gains, and its frictional force parameters are exactly the same as used for NIASA in [9], as described in the preceding paragraph. A regular integral gain of 1 N/(s·μm) is used for VAN (as opposed to the nonlinear integral action used in NIASA).

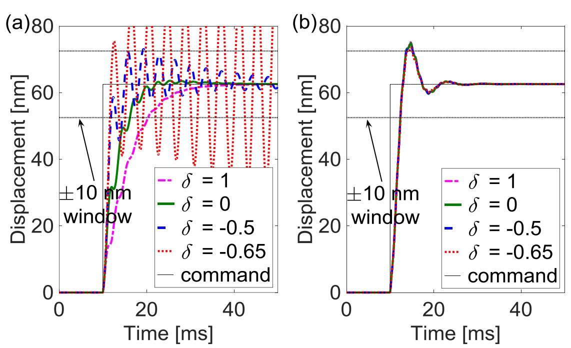

FIGURE 3. Settling results of (a) NIASA and (b) VAN in response to a 62.5 nm step command using different values of initial contact stiffness in the Dahl model. Note that A = 3 N and f = 500 Hz for VAN.

Table 1. Comparison of settling times of NIASA and VAN into the ±10 nm window shown in Figure 3 for various values of δ.

Method	Settling Time [ms]			
	δ = 1	δ = 0	δ = −0.5	δ = −6.5
NIASA	10.3	6.2	9.5	N/A
VAN	5.2	5.2	5.1	5.1

Figure 3 compares the settling responses of NIASA and VAN to a 62.5 nm step command used by Bucci et al. [9]; a ±10 nm window is used as the settling window. A multiplicative uncertainty parameter $\delta \in [-1, \infty)$ is introduced by Bucci et al. [9] into the contact stiffness σ of the Dahl model described by Eq. (3) to help demonstrate the robustness of NIASA to changing friction. It is observed that NIASA is indeed stable within the parameter band $\delta \in [-0.5, 1]$ that is presented in [9]. However, its settling performance varies significantly as δ deviates from its nominal value of zero as shown in Figure 3(a). Notice that the system with NIASA experiences severe oscillations for δ = −0.5, and suffers from a limit cycle with large amplitude for δ = −0.65, causing it to not settle. On the other hand, as shown in Figure 3(b), VAN (with A = 3 N and f = 500 Hz) demonstrates remarkable robustness and settling performance in the presence of varying friction.

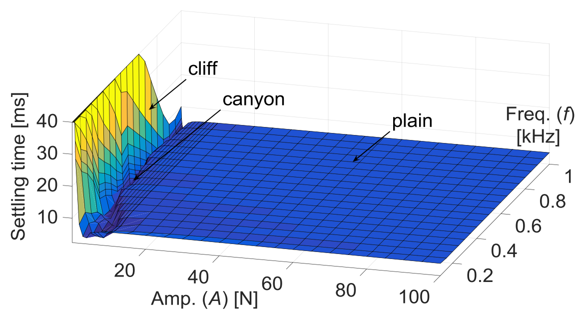

FIGURE 4. Effect of dither amplitude (A) and frequency (f) on settling time for VAN stage

It is of interest to study the effect of A and f on the settling performance of VAN. Figure 4 shows the settling times of VAN as functions of A and f for the same test case as in Figure 3 (with δ = 0). The settling time characteristics can be said to have a cliff, a canyon and a plain. At very low amplitudes and frequencies, the addition of dither produces little or no effect in reducing settling time. But beyond a certain critical frequency, there is a sudden drop in settling time over the cliff to its lowest levels (i.e., the canyon). It is observed that this critical frequency mainly depends on A. As A (and to some extent f) is increased further, the settling time increases slightly after which it remains largely unchanged (i.e., the plain). In terms of robustness, the plain is excellent because it provides a wide range of A and f values to choose from without losing performance. The problem is that the plain occurs at relatively higher A or f values, which could pose challenges with regard to heat generation and bearing wear. The canyon provides optimal settling times at relatively lower A and f values than the plain. Therefore, operating within the canyon region could provide huge benefits with regard to the reduction of heat and wear. However, the challenge is that the canyon is very narrow and close to the cliff; settling times could rise sharply (up to 5 times in Figure 4) if the critical amplitude or frequency is crossed.

In the results presented in Figures 3(b) and 4, because $F_{f1} = F_{f2} = F_f$ is assumed, the reaction forces due to dithering perfectly cancel out, leading to zero vibration at the stage. If $F_{f1} \neq F_{f2}$, unequal reaction forces are generated and the stage experiences continuous vibration which may cause it to not settle. As discussed in the previous section, such unwanted vibration can be mitigated by regulating the applied dither and/or by injecting a compensating force F_{comp} via the stage's servo controller. In this preliminary work, we evaluate a simple regulation technique where dither is applied and then suddenly turned off after duration T, starting when the reference command reaches the target position. Such an approach is suitable for point-to-point positioning tasks where high precision is only required after the target position is reached.

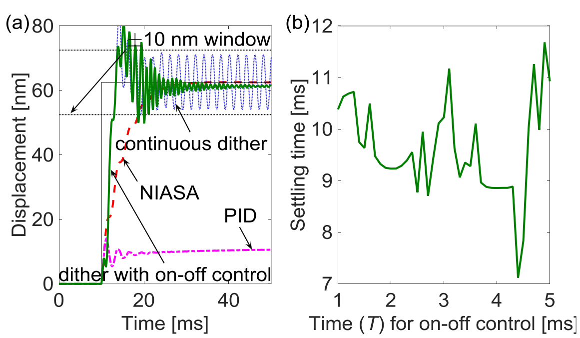

FIGURE 5. (a) Settling results of VAN in response to a 62.5 nm step command with imperfect cancellation of dithering reaction forces (compare with Figure 3(b)); (b) effect of time (T) on settling time for VAN

Let us re-consider the scenario shown in Figure 3(b) for VAN, but with $\delta = 1$ for F_{f1} and $\delta = 0$ for F_{f2}. Figure 5(a) compares the settling behavior of NIASA and VAN with and without on-off dither control to that of a regular PID controlled stage. Notice that without on-off dither control, VAN stage settles into the ±10 nm window in 9.3 ms while NIASA settles in 8.7 ms, which are both huge improvements compared to the regular PID which does not settle within the simulation time of 50 ms. However, because of the imperfect cancellation of reaction forces, VAN continues to vibrate as long as dither is maintained. The lingering vibration can be eliminated by shutting off dither as shown in the figure for T = 3 ms. Notice, however, that on-off control introduces some transients before the vibration dies down completely. The transient vibration could be reduced by making the on-off control less abrupt or if the stage has extra damping (as will be seen later in the experiments).

Figure 5(b) shows the settling times of VAN with on-off control for various values of T ranging from 1 to 5 ms. The observed fluctuation in settling time as T changes is partly due to the aforementioned transient vibration as well as the fact that the stage is at different positions (relative to the target position) when dither is turned off. Nonetheless, the deformed springs provide extra forces to overcome pre-rolling friction after dither is turned off, leading to much faster settling of the stage to the target position compared to the regular PID.

PROTOTYPE DESIGN AND EXPERIMENTS

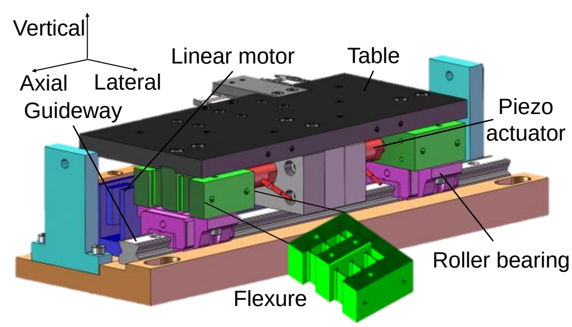

FIGURE 6. CAD model of a prototype VAN stage.

A prototype VAN stage is designed according to the general concept described in the previous section. Figure 6 shows the CAD drawing of the prototype, which is designed to have a moving mass of about 2 kg and a travel range of 50 mm. The stage is guided by a set of high-rigidity radial type linear ball bearings, riding on a super-precision grade rail. An ironless linear motor with 23 N continuous force is selected to drive the stage. The table position is measured using a 4.88 nm-resolution linear encoder. A pair of preloaded piezo actuators is selected to provide the dither force; each actuator has a travel range and blocking force of up to 15 μm and 300 N, respectively, with a maximum operating frequency of 6000 Hz.

A simple flexure hinge, made of AISI 304 stainless steel, is used to connect the table to each of the roller bearing. Its role is to provide sufficient compliance in the direction of dithering while remaining rigid in other directions. Table 2 compares its stiffness values in different directions (obtained using SolidWorks® finite element analysis) with those of the linear bearing. With an axial rigidity of 6.9 N/μm, the flexure can provide around 11 μm of displacement (with 77 N force) at the maximum operating voltage of the piezo actuators (i.e., 100 V). Notice from Table 2 that the vertical and lateral stiffness of the flexure are much higher than its axial stiffness. As a result, the combined stiffness of the flexure and linear bearing in the vertical and lateral directions have same order of magnitude as those of the linear bearing alone. It is important to note that at an applied load of 77 N, the highest maximum von Mises stress of the flexure is 43 MPa, which is much lower than the endurance limit (203 MPa) of 304 stainless steel. So, even at its worst-case loading, infinite fatigue life is guaranteed for the flexure.

Table 2. Stiffness of linear ball bearing and flexure (N/μm).

	Axial	Vertical	Lateral
Bearing	N/A	175	58.3
Flexure	6.9	310	331
Combined	6.9	111.9	49.6

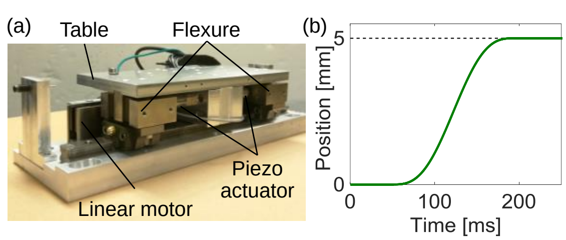

FIGURE 7. (a) Assembled VAN stage; (b) commanded position of a typical 5 mm move-and-settle operation.

Figure 7(a) shows an in-house-built prototype of the VAN stage. A typical 5 mm “move-and-settle” profile is used as the reference trajectory as shown in Figure 7(b). It has maximum acceleration/deceleration of 1500 mm/s^2 with a maximum velocity of approximately 70 mm/s. Only the settling portion, after the target position is reached, is considered in this paper. A PID controller with velocity and acceleration feed forward is used to control the stage. The PID controller is tuned to achieve a closed loop bandwidth of about 195 Hz. It is implemented using a real time controller (dSPACE, DS1007) with current commands sent through a PWM amplifier. The two piezo actuators are controlled in open loop by sending sinusoidal commands through their voltage amplifiers.

The friction behavior of the prototype stage has been found to not conform to the Dahl model, so NIASA is not a suitable benchmark for experiments. Therefore, the performance of VAN is evaluated in experiments by studying the settling behavior of the prototype stage with and without dither. Figure 8 compares the settling performance of the stage into a 100 nm window with and without dither. Without dither, the stage takes 55.1 ms to settle. Dither with peak-to-peak amplitude of 20 V (corresponding to 15 N) at 500 Hz is added and, as expected, the stage experiences steady state vibrations due to imperfect cancellation of the reaction forces. The imperfect cancellation of reaction forces is caused by non-idealities in the stage, like differing friction forces on each bearing and slight differences in the performance of each piezo actuator and amplifier. The on-off control used in the simulations is applied (with T = 7.5 ms), causing the stage with dither to settle within 19.4 ms, which is 64.8% shorter than the case without dither. Notice that no significant transients are generated by the abrupt switching; this is in part due to the higher damping provided by the roller bearings, compared to the model used in simulations.

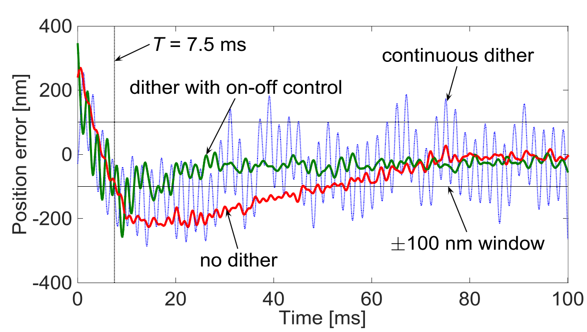

FIGURE 8. Typical settling response of no dither, continuous dither and dither with on-off control (T = 7.5 ms).

Figure 9 plots the settling performance of the prototype stage with on-off dither control for various values of T, in comparison with the case without dither. It is observed that with and without dither, the settling performance of the stage varies a bit, due to differences in friction from position to position along the travel of the stage. The plots in Figure 9 show the mean settling times based on 20 trials at random positions of the table within its travel range; the error bars indicate one standard deviation. Without dithering, the mean settling time is 53.3 ms with a standard deviation of 4.8 ms, which shows the slow settling performance in comparison with the length of the reference trajectory (i.e., 100 ms). With on-off control, the stage with dither is able to achieve a mean settling time of 20.4 ms at T = 7.5 ms (with a standard deviation of 4.1 ms), which is 61.7% less than the case without dither. Apart from this optimal value, notice that with dither the system performs consistently better than the no-dither case for all values of T. Moreover, the proposed method is robust, considering that the stage is at random positions when dither is turned off for each trial.

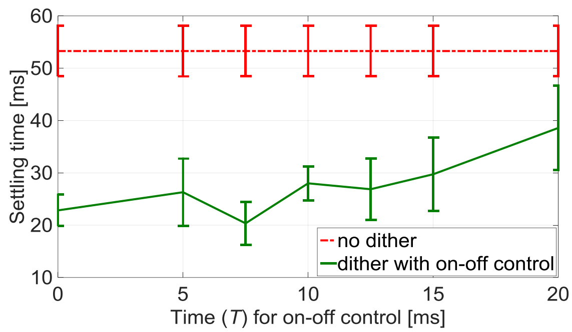

FIGURE 9. Comparison of mean settling times into the ±100 nm window for no dither and on-off controlled dither with different T

CONCLUSIONS AND FUTURE WORK

In this paper, a novel approach for improving settling performance of roller bearing nanopositioning stages using high-frequency vibration (or dither) has been presented; it is called vibration assisted nanopositioning (VAN). It has been shown using simulations that VAN achieves superior performance and robustness compared to a model based friction compensation. A prototype VAN stage has been designed and built. Preliminary experiments conducted using the designed prototype (with a rudimentary on-off dither control technique) have demonstrated up to 61.7% reduction in mean settling time in point-to-point positioning. Future work will investigate advanced dither and stage control techniques, based on rigorous theoretical analyses, to help optimize the performance and robustness of VAN.

ACKNOWLEDGEMENT

The authors are grateful to Professor Shorya Awtar and Mr. Deokkyun Yoon for providing valuable feedback on the prototype design and to Aerotech Inc. for donating some of the key components used in designing the prototype. This work is partially supported by the Rackham Summer Award of the University of Michigan, awarded to the first author.

REFERENCES

[1] Lan H, Ding Y, Liu H, Lu B. Review of the Wafer Stage for Nanoimprint Lithography. Microelectron. Eng. 2007; 84: 684–688.

[2] Kim W, Trumper DL. High-precision Magnetic Levitation Stage for Photolithography. Precis. Eng. 1998; 22: 66–77.

[3] Sitti M. Survey of Nanomanipulation Systems. Proc. 2001 1st IEEE Conf. Nanotechnology. 2001; 75–80.

[4] Melngailis J. Focused Ion Beam Technology and Applications. J. Vac. Sci. Technol. B: Microelectron. Nanom. Struct. 1987; 5: 469.

[5] Maeda Y, Iwasaki M. Rolling Friction Model-based Analyses and Compensation for Slow Settling Response in Precise Positioning. IEEE Trans. Ind. Electron. 2013; 60: 5841–5853.

[6] Armstrong-Hélouvry B, Dupont P, De Wit CC. A Survey of Models, Analysis Tools and Compensation Methods for the Control of Machines with Friction. Automatica. 1994; 30: 1083–1138.

[7] De Wit CC, Lischinsky P. Adaptive Friction Compensation with Partially Known Dynamic Friction Model. Int. J. Adapt. Control Signal Process. 1997; 11: 65–80.

[8] Thomsen JJ. Some General Effects of Strong High-frequency Excitation: Stiffening, Biasing and Smoothening. J. Sound. Vib. 2002; 253: 807–831.

[9] Bucci BA, Cole DG, Ludwick SJ, Vipperman JS. Nonlinear Control Algorithm for Improving Settling Time in Systems with Friction. IEEE Trans. Control Syst. Technol. 2013; 21: 1365–1373.

[10] Dahl P. A Solid Friction Model. Aerosp. Corp. El. Segundo, CA. 1968; 158.