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A novel drive and control method for piezoelectric motors in microscopy stages

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Abstract
A sophisticated driving and motion control method is presented for a high precision positioning system that is motorized with piezoelectric resonance drive motors. Friction-induced vibrations can initiate slow motion noise (SMN) since the moving speed of a microcopy stage is < 2.0 mm/s. SMN is not only undesirable for a user but it also reduces scanning accuracy of an X–Y microscopy stage. Nonlinear characteristics of friction at contact surfaces are the main root cause for the SMN, which also substantially affects the working atmosphere of the user. To eliminate both SMN and tracking errors in microscopy stages, a novel driving method was proposed for ultrasonic piezoelectric motors. Using a dual-source dual-frequency (DSDF) driving method, which reduces the nonlinear phenomenon of transition between static and dynamic friction at the stator-slider contact points, control of the smallest incremental movement was significantly enhanced. As a result, the amplitude and direction of vibration of the tip that is attached on the stator element generate modulated movements that reduce the acceleration acting on the slider; thus, smooth movements at low speeds were possible. A proportional integral derivative (PID)-based state window control algorithm, which optimized individual parameters and changes via current velocity, was investigated for various motion states.
In this study, adaptive position control methods were combined with the above-mentioned DSDF driving method, which then allowed us to use one unique parameter set for all applications, such as fast step-settle, dynamic positioning, high-speed scanning, and sinusoidal path, that were followed in order to fulfill all of the requirements of the different microscopy stages. We can manage to control both axes of the microscopy stages silently using the aforementioned low velocities with a minimized position tracking error.

Keywords: Adaptive control, piezoelectric motor, microscopy stage, noise elimination, positioning

1. Introduction

For the last two decades, it has been preferable to drive high-end motorized microscopy stages by piezo motors rather than electromagnetic ones due to the several advantages of the piezo motors: slim size, high accuracy, self-locking property without requirement of additional energy, fast response and noiseless operations [1, 2]. The piezo linear motor with ultrasonic resonance drive directly moves the platform of the stages over a wide velocity range. Moreover, piezo motors have exceptional long-term stability. However, nonlinearities of friction medium between stator and rotor of piezo motors can degrade the basic operation performance. Position tracking accuracy at low-speed scanning and positioning time at step and settle applications for microscopy stages are two significant features that are dependent on friction types and conditions at contact surfaces between piezo motor and the slider. Intelligent driving and control methods can be applied to drive piezo motors to get better performance for such use cases [3, 4]. An adaptive PID controller was introduced by using state windows together with DSDF drive was then tested for PIline® motors to enhance tracking and positioning accuracies. In this work, a PIline® piezo motor with driving methods is first presented. Later, a control algorithm together with block diagram is explained. Last, test results from different microscopy stages with comparisons are described.

2. PIline® piezo motor

The stator of the PIline® piezo motor operated in resonance mode has a rectangular shape made up of bulk PZT material (actuator) which is produced by Physik Instrumente (PI). A ceramic tip (pusher) is bonded at the middle of one side of the stator. A holding mechanism with springs was designed to enclose and apply a prestress to the friction bar glued stator to come into contact with the movable rotor surface guided by a bearing. Three excitation electrodes were sputtered on two main surfaces, one of which is covered completely. The opposite surface was divided in to two equal sectors [5]. The piezo motor can then be operated at one of its resonance frequency to generate elliptical oscillations at the tip (Figures 2 and 3).

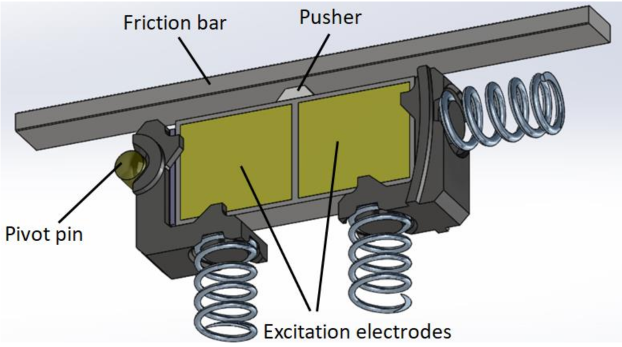

Figure 1. (Structure of PIline® piezo motor, [5])

3. Driving methods

The frequency (Impedance and phase) response of the PILine® piezo stator was measured with the Agilent Impedance Analyzer 4294A in order to find suitable resonances for usable vibration modes. The piezo element as a stator that we used in the piezo motor has a rectangular geometry of 25 mm × 11 mm × 4 mm. In these measurements, one of separate electrodes was loaded with a low sweep signal, and the second electrode was kept free. Measurements indicated two resonance frequencies in the bandwidth between 150 and 180 kHz (Figure 2). The friction tip performed an oblique or narrow elliptical movement at f_1, which was the main operating mode. The tip performs a tangential back and forth movement at f_2 [6].

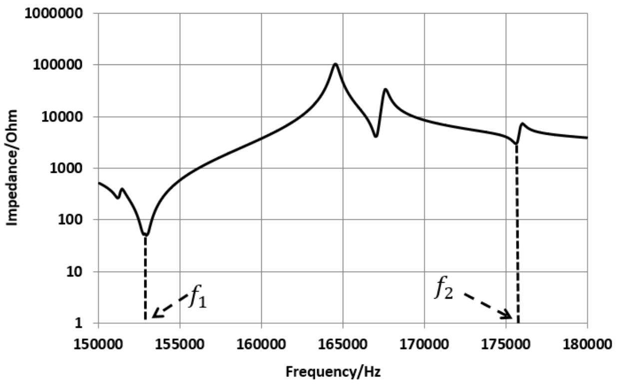

Figure 2. (Impedance spectrum of the piezoelectric vibrator between 150 and 180 kHz. The friction tip performs an oblique or narrow elliptical movement at f_1. The tip performs a tangential back and forth movement at f_2 [6].)

3.1. One source drive

In the one source drive, one of the separate electrodes of the piezo stator was loaded with its resonance frequency f_1 in a sine waveform, and the second separate electrode kept free. The common electrode on the opposite was grounded. By using a one-source drive stator held with spring damping mechanism, a planar mode at f_1 was generated, which was approximately 155 kHz. The stator tip formed elliptical oscillations, which were transferred to the slider (Figure 3). The direction of the movement could be altered by switching the driven electrodes.

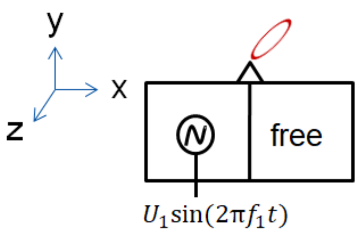

Figure 3. (One source drive with PIline® stator)

By using the one-source drive, the piezo motor generated constant elliptical oscillations in the same vector direction. High velocities could thus easily be achieved. However, continuous movement at low velocities < 2 mm/s could not be performed appropriately since nonlinear friction dominates at low velocities. Nonlinearities could not be overcome with linear constant oscillations. Therefore, tracking errors could not be reduced due to the stop and go type motions driven by this linear PID-based closed-loop control. Such stop and go type motions led friction-induced vibrations accompanying undesirable SMN at a low speed as well. Additionally, minimum incremental motion cannot be reduced adequately to get precise positioning. That is why step and settle movements occasionally take longer.

3.2. DSDF drive

The piezoelectric stator vibrated with two eigenmodes, which was superposed in order to supply mixed oscillations by using DSDF drive. Movements of the tip had two sinusoidal trigonometric components with the loading of two different voltage amplitudes (U_1, U_2) and two operating frequencies (f_1, f_2). Therefore, directions of movements were not constant and modulated with respect to time (t). Variations between two eigenfrequencies, which were dependent on the geometry, and mass of piezo elements were mostly not in the audible region. The difference between two applied frequencies (f_2 and f_1) should ideally be set to 20 kHz to obtain a correlation with closed loop servo frequency of the most digital controllers [4]. The modulated oscillations of the friction tip are shown in Figure 4.

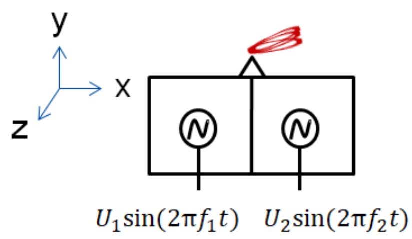

Figure 4. (DSDF drive with PIline® stator)

As the frequency difference between f_2 and f_1 was synchronized to the closed loop servo frequency, the slider started to perform a smaller continuous and finer microscopic movements. Therefore, low velocity tracking was noiseless and minimum incremental motion could be further reduced. Consequently, positioning with lower tolerance bands could be accomplished faster.

4. Motion control algorithm

The motion control in block diagram for each axis of microscopy stage is presented in Figure 5. The control unit was based on an adaptive PID state windows which depend on not only position error but also commanded velocity. Offset logic block was implemented in the control loop in order to reduce the time requirement to overcome both the friction-dependent breakaway force at the beginning of the motions and velocity reversals.

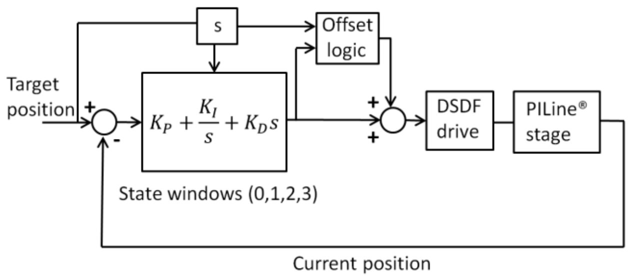

Figure 5. (Block diagram of the position control system for microscopy stage)

Switching between motion states and corresponding parameter sets in state windows occurs depending on the current velocity and variation between current and target position of the motor. PID parameter values for motion state could be automatically adapted to the specified target velocity (v_T). Details of the individual states included several steps:

Control state (2, Motion) remains active until the current velocity (v_C) has the value less than a minimum target velocity $(v_{T,min})$ and the trajectory is finished. PID parameter adjustment takes place whenever the target velocity in a range defined by maximum target velocity $v_{T,max}$ and $v_{T,min}$. Since the state window algorithm aims to optimize slow motion performance; the values of PID terms K_j at the lower limit of target velocity could be specified. The relationship of adaptive PID parameters with current velocity is given in equation (I).

$$K_j = K_{j,min} + \frac{(K_{j,max} - K_{j,min})}{log(v_{T,min}/v_{T,max})} log(v_C/v_{T,max}) \qquad (I)$$

in which *j* is a variable for P, I and D parameters. Maximum and minimum values of *j* are $K_{j,max}$ and $K_{j,min}$, which are set in the motion state.

Control state (1, End Position) is the state for the slower movement of the motor to reach the target position. This state is active until the movement reaches the on-target state, which is defined with the position tolerance band around the target position. The motion is accomplished when the specified delay time for setting the on-target state has expired.

Control state (0, Target) is the state in which the motor holds the axis at the target position. The control state is active as long as the position error is within the position tolerance band specified by parameters. As soon as the current position leaves this zone, the End Position state becomes activated again to move the axis back to target.

Control state (3, Global state) is activated to reduce the vibrations during the End Position and Target states when the current velocity exceeds the threshold value defined by a parameter. If the velocity fails below half of the threshold value, the state is switched back to End Position or Target state.

5. Test results

Fig. 6 shows the PIline® X–Y inverse microscopy stage U-761.25 together with C-867.2U2 and a joystick. The stage has optical incremental encoders, which have an interpolated resolution of 10 nm. The U-761.25 microscope stage was designed for excellent stability and high precision positioning applications. It has a low profile height [7]. The tests with this stage were performed under a laboratory condition at 22 °C environment temperature and a relative humidity of 50%. The stage has a travel range of 25 mm × 25 mm. The DSDF driving method was implemented as a firmware module in the controller.

Figure 6. (U-760 PIline® inverse microscopy stage with C-867.2U2 controller and Joystick)

5.1. Low velocity scanning

One of the important features of microscopy stages is the slow motion scanning capability with small position tracking errors. Figures 7 and 8 show the scanning performance of U-760 PIline® microscopy stage with 600 g dummy load mounted on the Y axis. The constant velocity in closed loop control was set to 0.05 mm/s at which piezo motor was operated in the nonlinear friction region. The microscopy stage with one source drive showed non-continuous movements. Tracking errors during the movement was measured to be about ± 250 nm. Smoother movements by changing PID parameters could not be achieved. Unpleasant noises and SMN was heard during low velocity scanning (Figure 7).

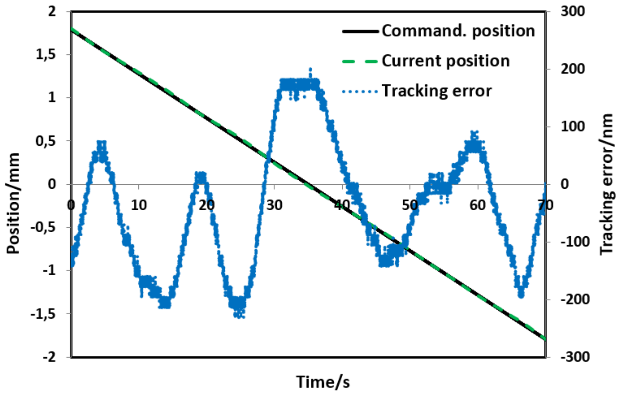

Figure 7. (Low velocity motion and tracking error with U-760 PIline® microscopy stage with one source drive)

In spite of having friction nonlinearities, the microscopy stage with the proposed control method with DSDF drive ran in the same ± 1.8 mm travel range with only a ± 50 nm maximum tracking error. The movement was extremely smooth and chatter-free (Figure 8). In addition to this characteristic, no SMN was observed during the tracking of low velocity scanning.

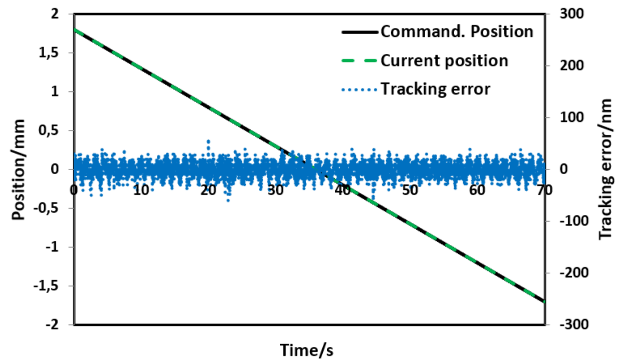

Figure 8. (Low velocity motion and tracking error with U-760 PIline® microscopy stage with a DSDF drive and state window controller)

5.2. Step and settle, positioning

Step and settle time is the time that has elapsed until a stage or a motor reaches a target value with a specified tolerance band. First, we performed a step and settle positioning test with U-760 PIline® microscopy stage with 600 g dummy load. The stage was commanded with relative movement of 0.1 mm (step width) randomly over the travel range. The tolerance error band at the target position was set to 100 nm. Figure 9 shows the positioning test results of 1000 random step and settle measured at the Y-axis of the microscopy stage by using the one-source drive together with state window control. The black curve is the trajectory commanded by trajectory generator with 0.1 mm step width. The green and blue curves are reactions of the motor as actual positions and position errors of 1000 tests, respectively. As is seen in the figure, the horizontal axis was the time in seconds, the vertical axis on the right-hand side was the relative position, and the left-hand side was the position error expressed as mm. The vertical red line was the mean value of the positioning (settling) time for these 1000 tests. The mean settle time with one source drive was about 97.5 ms. A lot of time elapsed during the second part of the trajectory which the piezo motor moved in a stop and go manner (stick-slip) due to the nonlinearity of friction as previously described.

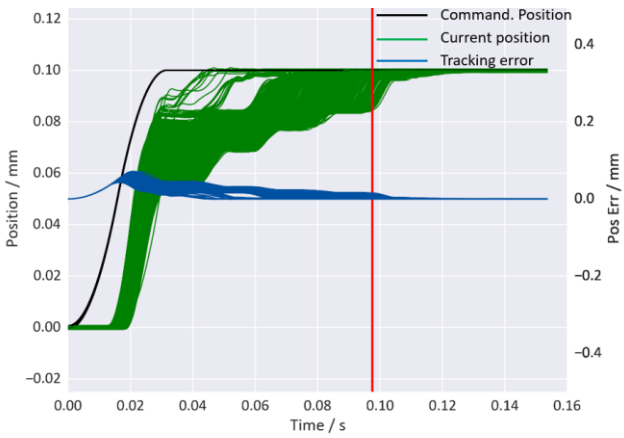

Figure 9. (Step and settle test with U-760 PIline® microscopy stage driven by one source drive)

Second, the same positioning tests were repeated with the microscopy stage under the same environmental conditions. We applied the DSDF drive in this case. Similar PID state window and adaptive control parameters were used in one source drive were implemented in DSDF drive as well. Figure 10 shows the results of 1000 step and settle positioning. One can easily determine the characteristics of green curves for which positioning took relatively less time. Stop and go movements seen in one source drive were rarely observed by DSDF drive since the amplitude and the direction of vibration of the stator tip modulated movements that reduced the acceleration acting on the slider within a servo period of digital controller. Thus, fine movements near the target positions were possible. The adaptive PID-based state window control algorithm enhanced controllability during positioning with optimized parameters at various motion states that changed with position error and current velocity. We reduced the positioning time of microscopy stage with 600 g load by half by using DSDF drive. Mean settle time measured with DSDF drive was about 50.8 ms.

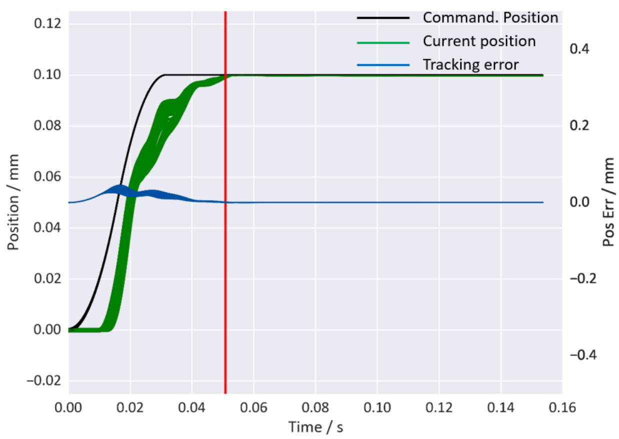

Figure 10. (Step and settle test with U-760 PIline® microscopy stage driven by DSDF drive)

6. Conclusion

The piezo motor-based microscopy stage is operated with DSDF drive by using two eigenfrequency modes to obtain particular oscillations, which suppress friction nonlinearities at the contact surface. Thus, the piezoelectric motor continuously actuates at lower velocities and precisely without any noise from friction-induced mechanical vibrations. Oscillation amplitudes and directions will not be constant due to the two frequency modes. The difference between the two excitation frequencies lies in the DSDF driving method that is synchronized to the servo sampling frequency of the closed loop control. Linear position control of the existing one source drive and ultrasonic motors can lead to friction-induced vibration, higher tracking errors, and noise at velocities < 2 mm/sec Positioning time with DSDF drive and state windows in the adaptive position control in the step and settle test of microscopy stage can be reduced by half compared to the one with the single source drive.

The DSDF driving method with an adaptive state window position control was also tested at low velocity scanning. The control algorithm together with DSDF provides robust and simplified position control, especially over slow driving speeds without sound and performance degradations. Results showed a silent and smooth movement with at a velocity < 2 mm/s. The test results indicate that maximum tracking error at 0.05 mm/s velocity was < 50 nm.

When the slider is operated at high speed, the operation of single source or DSDF drives are equivalent. Because the mode that the second source excited at 20 kHz high is a weaker, the effect of second source is relatively small to the slider operation. In general, second source driving is against the normal operation of the slider and second source driving cause the displacement at the pusher end to be modulated. This negative effect at low speed is used as a benefit for obtaining controllable small steps. When the slider makes a small step in a servo control loop, actuator force reduces after a small step. At low speed, it is possible that efficiency of the motor would be decreasing, however, ability of making small steps are more important.

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