Preprint. Published in: Proceedings of 10th International Workshop on Piezoelectric Materials and Applications and 8th Energy Harvesting Workshop, Hannover, Germany, July 2013 – pages 16-18

High-Velocity Slip-Slip Operation of Piezoelectric Inertia Motors – Experimental Validation

Matthias Hunstig, Tobias Hemsel, Walter Sextro
Mechatronics and Dynamics, University of Paderborn, Germany
matthias.hunstig@upb.de

Abstract

It has been shown previously that “slip-slip” operation of piezoelectric inertia motors allows higher velocities and smoother movements than classic “stick-slip” operation. One very promising driving option is to use a superposition of multiple sinusoidal signals. In this contribution, previous theoretical results are validated experimentally. The results confirm the theoretical result that for a given maximum frequency, usually defined by the actuator characteristics, a signal with high fundamental frequency and consisting of two superposed sine waves leads to the highest velocity and the smoothest motion. This result is of fundamental importance for the further development of high-velocity piezoelectric inertia motors.

Key words: Piezoelectric inertia motor, stick-slip motor, driving signal, velocity, smoothness

Drive Signals for High-Velocity Inertia Motors

Piezoelectric inertia motors, also known as “stick-slip-drives”, use the inertia of a body to drive it by means of a friction contact in a series of small steps. These steps are often assumed to involve stiction and sliding, but inertia motors can also operate without phases of stiction. Different researchers have presented inertia motors using such a “slip-slip” mode of operation in the last years, e. g. in [1–3]. But the principal advantages, disadvantages and limitations of these two modes of operation have only recently been investigated by the authors of this contribution using a theoretical model [4, 5]. One result of the investigation was that “slip-slip” operation allows higher velocities and smoother movements than classic “stick-slip” operation.

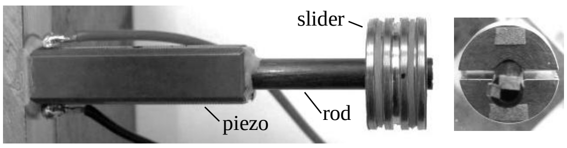
Both “stick-slip” and “slip-slip” operation can be realised with a variety of drive signals. For high velocity, the displacement profile of the stator of an inertia motor would ideally follow a parabolic sawtooth signal [4]. But such signals are hard to obtain, especially at high excitation frequencies. One very promising drive signal for high-velocity inertia motors is the superposition of multiple sinusoidal signals, i. e. harmonics. Such signals contain only a few frequencies and thus do not require high-bandwidth actuators. Phase and amplitude of the harmonics can be determined from the ideal signals [4]. With an appropriately designed transducer, actuation with such signals can also make use of resonant effects, as shown for example in [3, 6, 7]. With a transducer of limited bandwidth, a trade-off between a high drive frequency and a large number of harmonics has to be made. A systematic theoretical investigation of inertia motors driven with such signals has been performed recently and it has been found that for a given maximum frequency, a signal consisting of two superposed sine waves leads to the highest velocity and the smoothest motion [5]. In this contribution, these results are validated experimentally.

Model

For the calculations, the same simple model of an inertia motor as in earlier publications [4, 5] is used. It assumes a rigid driving rod and uses a kinetic friction model, i. e. the coefficient of friction depends only on the relative velocity between rod and slider. The parameters of the friction model have been obtained experimentally.

Experimental Setup

For the experimental investigation, a simple inertia motor has been built up: Its stator consists of a piezoelectric multilayer actuator with a rod made of carbon fibre reinforced plastic glued to one of its ends. The other end of the actuator is glued to a massive steel block. The cylindrical brass slider moving along the rod is cut into two halves which are held together by rubber bands providing the normal force in the friction contact. Figure 2 shows photographs of the motor. It has a total length of about 52 mm, the slider has a mass of 6.9 g. The movements of rod and slider are measured using laser vibrometers.



a) top view b) front view

Fig. 2: Investigated inertia motor

The signals used in the experiments have 2, 3, or 4 harmonics with frequencies between 578 Hz and 9250 Hz. The excitation voltage is chosen so that the rod has a stroke of 15 µm, see fig. 3. Figure 4 shows a frequency sweep of the mechanical admittance v/u of the stator, where $v(t)$ is the velocity of the rod and $u(t)$ is the excitation voltage. The desired stator displacement signals can be obtained only if the electric driving signal accounts for the stator dynamics. This is achieved in two steps: First, the desired signal is passed through an inverse linear model of the stator dynamics derived from the frequency response shown in fig. 4, as described in [8]. The stator is then excited using the obtained electrical signal. Due to the nonlinearities of the system such as hysteresis and amplitude dependence, the desired displacement profile is typically reached only roughly with this signal. Thus, in a second step, amplitudes and phases of the harmonics of the measured rod displacement $x_R(t)$ are determined and the electrical signal is adjusted accordingly. If necessary, this step is repeated. Typically, amplitude and phase errors are below 1 %, respectively 1°, after one iteration cycle.

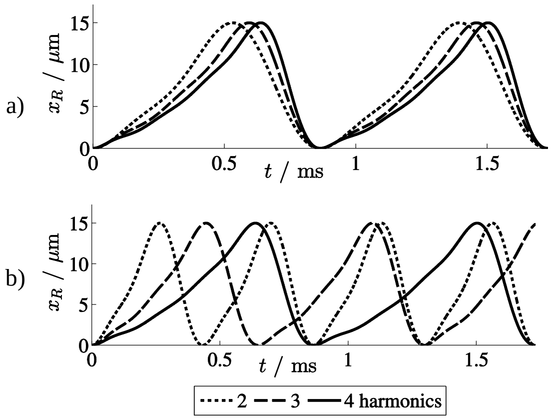


Fig. 3: Example excitation signals with a different number of harmonics n and a) the same fundamental frequency $f_0 = 1156$ Hz, b) the same maximum frequency $f_{max} = n \cdot f_0 = 4625$ Hz

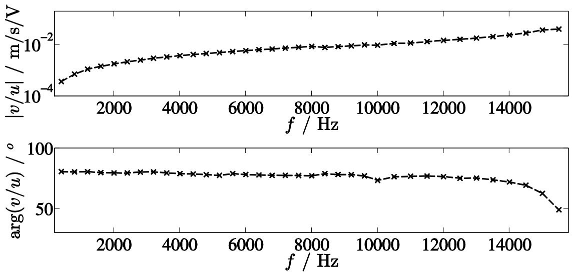


Fig. 4: Mechanical admittance v/u of the investigated inertia motor

Results

For three of the investigated maximum frequencies, fig. 5 shows the measured and the calculated steady state mean velocity of the slider and the smoothness of its movement as defined in [4]: The larger the smoothness indicator ς_∞, the smaller the fluctuation of the slider velocity around its mean value $\bar{v}_{S,\infty}$.

For each parameter set, about 8 measurements were carried out. The results generally lie close together, indicating a good reproducibility. There is a good fit between the experimental results and the simulation. At high fundamental frequencies f_0, i. e. high maximum frequencies $f_{\max}$ and low n, the measured velocities are very noisy, probably due to parasitic vibrations of the slider. This effect results in a larger variation of the data points and is possibly also the reason for the less good fit between measurement and model for these data sets.

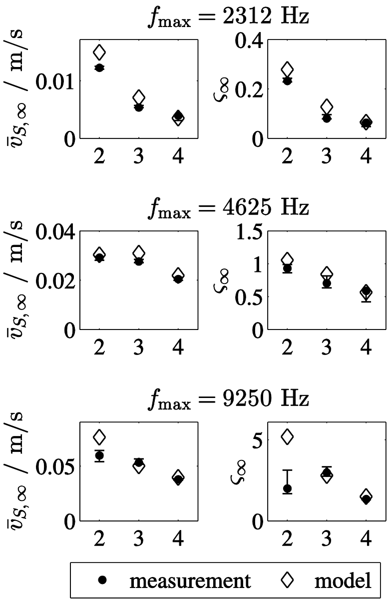


Fig. 5: Measured and calculated steady state mean velocity $\bar{v}_{S,\infty}$ and smoothness of the slider motion ς_∞ at different maximum frequencies and different numbers of harmonics

Conclusion

The experiments confirm the theoretical result [5] that at a given maximum frequency, a signal with high fundamental frequency and consisting of two superposed sine waves, as already realised in some resonant motors in literature [3, 6, 7], leads to the highest velocity and the smoothest motion. This result is of fundamental importance for the further development of high-velocity piezoelectric inertia motors.

In the full paper, the parameter identification for the friction models and the experimental procedure are explained in detail. Additional motor characteristics like the force generation potential, the efficiency, and the start-up time are also investigated. These characteristics also show a good agreement between measurement and model.

References

[1] Y. Okamoto, R. Yoshida, **Development of linear actuators using piezoelectric elements**, Electronics and Communications in Japan, Part 3, 81(11), 11-17 (1998), doi:10.1002/(SICI)1520-6440(199811)81:11<11::AID-ECJC2>3.0.CO;2-U

[2] J. Lee, W. S. Kwon, K. Kim, S. Kim, **A novel smooth impact drive mechanism actuation method with dual-slider for a compact zoom lens system**, Rev. Sci. Instrum. 82, p. 085105 (2011), doi:10.1063/1.3624701

[3] T. Nishimura, H. Hosaka, T. Morita, **Resonant-type smooth impact drive mechanism (SIDM) actuator using a bolt-clamped langevin transducer**, Ultrasonics 52(1), 75-80, (2012), doi:10.1016/j.ultras.2011.06.013

[4] M. Hunstig, T. Hemsel, W. Sextro, **Stick-Slip and Slip-Slip Operation of Piezoelectric Inertia Drives – Part I: Ideal Excitation**, Sensors and Actuators A: Physical (2012); doi:10.1016/j.sna.2012.11.012

[5] M. Hunstig, T. Hemsel, W. Sextro, **Stick-Slip and Slip-Slip Operation of Piezoelectric Inertia Drives – Part II: Frequency-Limited Excitation**, Sensors and Actuators A: Physical (2013); doi: 10.1016/j.sna.2012.11.043

[6] R. Bansevicius, V. Blechertas, **Multi-degree-of-freedom ultrasonic motors for mass-consumer devices**, J. Electroceram. 20(3), 221-224 (2008), doi:10.1007/s10832-007-9178-3

[7] T. Morita, H. Murakami, T. Yokose, H. Hosaka, **A miniaturized resonant-type smooth impact drive mechanism actuator**, Sens. Actuators, A 178, 188-192 (2012), doi:10.1016/j.sna.2012.02.017

[8] M. Hunstig, T. Hemsel, W. Sextro, **Improving the Performance of Piezoelectric Inertia Motors**, ACTUATOR 2010 Conference Proceedings, 657-661 (2010)