Investigation of vibro-impact dynamics in PILine® ultrasonic motors

Simon Kapelke*, Felix Hartenbach* and Wolfgang Seemann**
**Physik Instrumente (PI) GmbH & Co. KG, Karlsruhe, Germany*
***Institute of Engineering Mechanics, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany*

Summary. PILine® ultrasonic motors belong to the group of standing wave ultrasonic motors and, as common for this kind of drives, use certain eigenmodes of a piezoelectric actuator to generate motion. The motion of the actuator is transmitted to a moving slider by means of friction using a coupling element, which performs a high-frequency oblique or elliptical motion. Within this contribution, the possible onset of impact oscillations in standing wave ultrasonic motors is investigated. After introducing a basic motor structure, corresponding experimental results are presented accounting for low-frequency dynamics. Subsequently, a simple mechanical model for normal oscillations of the piezoelectric actuator is evaluated by means of numerical integration. The derived results are compared qualitatively to experimental observations and provide good insight into the relevant dynamics.

Introduction

Piezoelectric motors are commonly used in several commercial, industrial or research related applications. Depending on the specific driving principle, piezoelectric motors can be divided into different categories, such as ultrasonic, stepping or inertia type drives. Ultrasonic motors, and in particular standing wave ultrasonic motors, are known for their high dynamics and accuracy in motion and positioning while providing long travel ranges and self-locking capabilities at rest. These basic properties are achieved by exciting certain eigenmodes of one or more piezoelectric actuators, such that a coupling element attached to the piezoelectric actuator performs a high-frequency oblique or elliptical motion, which is transmitted to a linear or rotational slider by means of friction [1].
The underlying dynamic processes are highly non-linear and, among others, include electro-mechanical coupling, vibro-impact dynamics and friction. Nevertheless, some effort has been spent in the past in order to establish mathematical descriptions of the corresponding dynamics [2, 3]. While most publications assume quasi-static behaviour of the piezoelectric actuator, the exceptional role of actuator inertia properties and, accordingly, the possible onset of impact oscillations has been pointed out recently [4].
Within this contribution, both experimental and model-based investigations related to vibro-impact dynamics of standing wave ultrasonic motors are carried out. Based on the schematic structure of PILine® ultrasonic motors and corresponding experimental observations, a simple mathematical model is presented accounting for vibro-impact dynamics. The model can be investigated either by separating slow and fast system dynamics or in terms of direct numerical integration and, together with the experimental observations, gives good insight into relevant dynamic processes.

Basic motor structure and experimental observations

The basic structure of PILine® ultrasonic motors is depicted in Fig. 1 and contains a rectangular piezoelectric actuator (1) and the attached coupling element (2). Due to electrical excitation of the piezoelectric actuator, the coupling element performs an elliptical motion, which is transmitted to the slider (3) with horizontal guiding by means of dry friction. The actuator has a pre-stressed elastic foundation, while transverse motion is suppressed by a corresponding suspension (4).
Under certain driving conditions, many ultrasonic motors show undesired vibrations in the audible range, although typical driving frequencies can easily exceed 100 kHz. Among undesired noise phenomena, this behaviour can even cause a loss of performance and is mostly handled by using advanced driving or control techniques [5]. However, in terms of system modelling and for improved control design, deeper understanding of the corresponding dynamics is required.
A recent publication has pointed out the possible onset of impact oscillations resulting from the high-frequency motion of the piezoelectric actuator in combination with the non-linear contact mechanics between coupling element and slider [4].

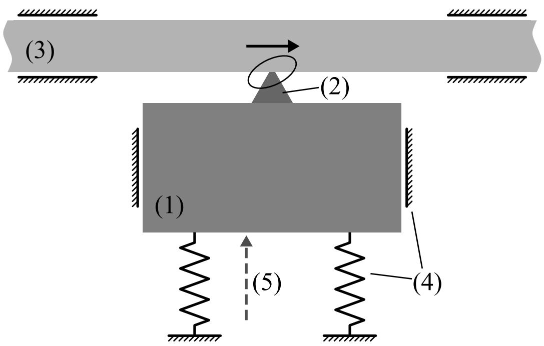

Figure 1: Schematic PILine® motor structure (1–4) and vibrometer measurement beam (5)

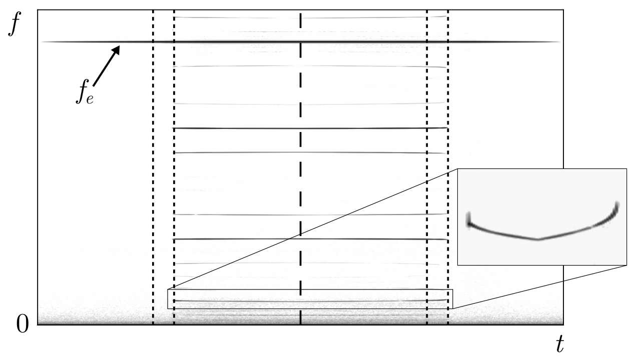

Figure 2: Experimental results for linearly increasing (first half) and decreasing (second half) excitation amplitude

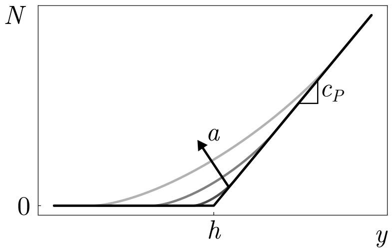

Figure 3: Average normal contact force for different excitation amplitudes

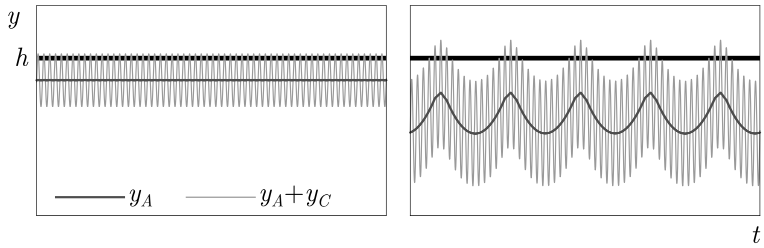

Figure 4: Exemplary solutions for different excitation amplitudes: floating type (left) and period-n solution (right)

Corresponding experimental results, where the normal motion of the piezoelectric actuator has been investigated using a *Polytec VibroFlex Xtra* laser vibrometer (5), are shown in Fig. 2. Herein, the frequency content of the normal actuator motion has been recorded, while increasing and decreasing the excitation amplitude at fixed driving frequency. Apart from the basic driving frequency f_e, the results contain several lower frequencies and other non-linear characteristics, which can be used to validate model-based approaches. Important observations are related to bifurcations, co-existing stable solutions, amplitude-dependent frequencies and the non-linear amplitude evolution.

Modelling approach and first numerical results

In order to simplify the mathematical description and focus on normal oscillations of the actuator, normal and tangential components are investigated separately. This approach appears suitable, since the friction type coupling of normal and tangential motion is mainly unilateral. According to the basic structure of the ultrasonic motor introduced before, the equation for normal actuator motion can be stated as

$$m\ddot{y}_A + d\dot{y}_A + c_A y_A + N = 0 \qquad \text{with} \qquad N = \begin{cases} c_P(y_A + y_C - h), & \text{contact} \\ 0, & \text{separation} \end{cases}. \tag{1}$$

Herein, y_A is the normal displacement of the actuator, m is the corresponding mass and d, c_A are damping and stiffness coefficients of the foundation. N is the normal contact force with local contact stiffness c_P, $y_C = a\sin\omega t$ is the high-frequency motion of the coupling element and h corresponds to the location of the slider.
The system can be investigated by using separate descriptions for slow and fast system dynamics. This approach results in a compact formulation for the slow dynamics and allows for further (semi-)analytical investigations, e. g. smoothing of the normal contact force as depicted in Fig. 3 or evaluation of the corresponding amplitude-dependent natural frequency. However, for a first qualitative comparison between model-based results and experimental observations, simple numerical evaluation appears more suitable. Fig. 4 shows two exemplary solutions of the system depending on the chosen parameters and initial conditions: The first one is a typical floating type solution without low-frequency motion and one contact phase per period of the excitation. This kind of solution is commonly regarded as the desired mode of operation of standing wave ultrasonic motors. The second solution is obtained for the same model parameters and initial conditions, but with increased excitation amplitude. The resulting motion can be referred to as a period-n solution of the system showing large low-frequency oscillations together with the high-frequency excitation. Herein, long separation phases can be observed and the interval between two contact phases is mainly determined by the low-frequency actuator motion.

Conclusions and outlook

The given results can be regarded as a first local analysis of the presented model showing possible mechanisms for the non-linear system behaviour observed experimentally. However, further investigations require a global analysis of the modelling approach and improved experimental validation. First results as well as practical experience indicate the importance of considering further compliant properties of the slider. Otherwise, many of the previously observed phenomena are limited to transient behaviour or minor basins of attraction. Nevertheless, the presented results give good insight into relevant dynamic processes and their impact on the basic driving principle of standing wave ultrasonic motors.

References

[1] Spanner, K., Koc, B. (2016) Piezoelectric Motors, an Overview. *Actuators* **5**: 6.

[2] Li, X., Yao, Z., Lv, Q., Liu, Z. (2016) Modeling stick-slip-separation dynamics in a bimodal standing wave ultrasonic motor. *Journal of Sound and Vibration* **382**: 140–157.

[3] Tsai, M.-S., Lee, C.-H., Hwang, S.-H. (2003) Dynamic modeling and analysis of a bimodal ultrasonic motor. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* **50**: 245–256.

[4] Kapelke, S. (2021) A vibro-impact approach to PILine® ultrasonic motors. *ACTUATOR, International Conference and Exhibition on New Actuator Systems and Applications 2021*: 93–96

[5] Delibas, B., Koc, B. (2020) A method to realize low velocity movability and eliminate friction induced noise in piezoelectric ultrasonic motors. *IEEE/ASME Transactions on Mechatronics* **25**: 2677-2687.