Subharmonic oscillations in PILine® ultrasonic motors

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Abstract. PILine® ultrasonic motors belong to the group of standing wave ultrasonic motors and 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, a typical noise phenomenon related to operation of standing wave ultrasonic motors is investigated by means of experimental observations and a model-based analysis of vibro-impact dynamics caused by the nonlinear interaction between coupling element and slider. After introducing the basic driving principle of standing wave ultrasonic motors and an appropriate model reduction, numerical parameter studies are carried out for the normal motion of the piezoelectric actuator. Depending on the chosen parameters, the results show significant subharmonic oscillations, which are in good agreement with the corresponding experimental observations.

Introduction

Although being commonly used in many different applications, ultrasonic motors can be very sensitive with respect to certain driving conditions, in particular when they are operated under open-loop conditions. Depending on the specific application, several undesired noise phenomena related to the operation of ultrasonic motors are known from literature, which are typically handled by using advanced driving or control techniques (e.g. [1]). However, improved understanding of the relevant dynamic processes is required in order to efficiently develop new ultrasonic motor and corresponding control structures.

Model-based investigations on ultrasonic motors are mostly carried out regarding their mechanical performance and neglecting the dynamics of the piezoelectric actuator (e.g. [2]). On the other hand, only few publications are known accounting for the nonlinear interaction between coupling element and slider as a possible mechanism for the onset of low-frequency vibrations (e.g. [3]). Within this contribution, subharmonic oscillations due to vibro-impact dynamics of the ultrasonic motor are discussed using experimental and model-based approaches.

Results and discussion

Under certain open-loop driving conditions, the PILine® experimental set-up under investigation generates a squealing noise although being operated in the ultrasonic frequency range. In order to investigate the corresponding dynamics, the normal motion of the piezoelectric actuator is measured using a *Polytec VibroFlex Xtra* laser vibrometer. The results contain significant vibrations below the ultrasonic excitation frequency f_e, which can be identified as subharmonic oscillations with base frequency $f_b = \frac{1}{n} f_e$.

For a corresponding model-based analysis, a simple model for the normal actuator motion y is given by

$$m\ddot{y} + d\dot{y} + c_A y + N = 0, \qquad N = \begin{cases} c_P(y + a\sin\omega_e t - h), & \text{contact} \\ 0, & \text{separation} \end{cases}. \tag{1}$$

Herein, m is the mass of the piezoelectric actuator, d and c_A are damping and stiffness properties of the normal actuator suspension and N is the normal contact force, which is determined using the local contact stiffness c_P. a and $\omega_e = 2\pi f_e$ are the excitation amplitude and angular frequency, respectively, and h corresponds to the location of the slider.

Over a wide range of parameters, the corresponding numerical results show decaying oscillations with a non-trivial frequency. Using an averaging approach to separate the slow system dynamics from the fast excitation, this non-trivial frequency can be identified as the natural frequency of an averaged system for the slow system dynamics. Herein, the non-smooth contact characteristics are replaced by an average normal contact force subjected to a smoothing effect due to the high-frequency excitation of the piezoelectric actuator. This kind of system behavior is considered as regular floating type operation of standing wave ultrasonic motors.

However, the numerical results also contain stable low-frequency solutions for certain parameters, which can be identified as subharmonic oscillations and show good qualitative agreement with the corresponding experimental results. In this case, the actuator performs a bouncing type normal motion, such that longer separation phases occur in contrast to the desired purely high-frequency motion. This behavior may cause the previously described undesired noise as well as reduced dynamics and performance of the ultrasonic motor.

References

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