INTRODUCTION

Miniaturization is a well known keyword in terms of scientific and technical progress. In regard to electronics and mechanical components, it is subject to the so called mechatronics. This leads to constant increasing requirements regarding tools and measuring equipment. To qualify, for example, structures below 13 nm, the measuring device must provide a resolution far below one nanometer.

Sub-nanometer resolution can be achieved by piezo actuator systems. The effect used by the well-known piezoelectric lighters-voltage generation when pressure is applied is reversible. The “inverse piezo effect” is to convert electrical energy to mechanical energy. In combination with a preloaded mechanical spring system, a displacement is the consequence of a voltage change. Since this effect is affected by great nonlinearity, a closed loop is needed for a positioning system which is based on piezo actuators. Developing a positioning system with sub-nanometer resolution is of course a challenge but will not be discussed here. It is presumed that positioning system and measuring device provide the required resolution.

In the following, the requirements concerning dynamic and static behavior of such a system are discussed. In particular with scanning applications, accurate and constant velocity and small tracking errors are essential.

REQUIREMENTS

A piezo actuator system in the form of preloaded mechanical spring system can be regarded as a one-mass-spring system.

According to experience, piezo actuator systems are damped inadequately. For that reason, the resonance of the system cannot be neglected with closed loop systems. Methods have to be found to avoid amplified movement at resonant frequency. Due to the inadequate damping it is of particular importance to consider distortion forces that are not excited by the piezo element.

It is possible to avoid exciting resonance by decreasing the closed-loop speed. But due to the dynamic requirements this is not tolerable. The requirements concerning a closed-loop piezo positioning system are as follows:

- High closed-loop bandwidth
- Low phase shift between target and real position
- High shape accuracy
- High distortion rejection (especially for the resonant frequency and higher frequencies)
- High curve constancy regarding the target signal
- Small tracking error

As mentioned above, the relation of position displacement to applied voltage is nonlinear which is mainly due to a hysteresis effect.
For open-loop systems the actual position depends on the past position and the gradient of voltage. The past position was dependent on the last preceding position and again on the voltage gradient. To describe a piezo hysteresis, hence a large memory would be needed to rebuild the sequences of past positions and voltage gradients. Thus for open-loop systems the position is never clear. In addition to this hysteresis effect, the position is affected by drift. To compensate these nonlinear effects it is therefore essential to close the loop using a position sensor signal. By closing the loop the system will be linearized statically. But in dynamic applications nonlinear effects will still occur. When a triangle target signal is applied, for example, the system will not produce a constant tracking error as expected for linear systems. The tracking error will change over time while the target signal has a constant slope. This behaviour results from the fact that the piezo systems velocity is changing while it should be constant. This is an unwanted effect for all applications assuming the piezo actuator system to be linear.

Thus a piezo actuator system can be described and classified by the following criteria:

- Relation of position displacement to applied voltage
- Resonant frequency

**APPRAOCH**

Since closed-loop bandwidth is limited, high-order nonlinearity has to be compensated by a method. The control method has to handle the resulting effects of the inadequate damped system and the relatively slow drift effects of the piezo actuator.

Assuming nonlinear effects are now reduced to a minimum, the plant of a piezo actuator system can be regarded as an inadequate third order system consisting of the inadequately damped part and the entirety of all well-damped parts like amplifier bandwidth, delays and sensor bandwidth.

The transfer function can be reduced to the following La Place description.

\[
F(s) = \frac{A}{1 + \frac{2 \cdot D \cdot s + \frac{1}{\Omega_0^2} \cdot s^2}{\Omega_0^2} \cdot \frac{1}{T_v \cdot s}}
\]

One method to avoid excitation of the resonance is to add a notch filter to the regulation variable \( y \). The disadvantage is that the distortion is still exciting the resonance, and by adding a notch filter exactly this distortion cannot be compensated. When analyzing the pole–null–diagram of the model a better method becomes apparent.
The ideal way is to shift the poles of the piezo actuator system into the well-damped pole area. Thus the amplification at the resonant frequency will be damped actively without elimination of any frequency components regarding the signals regulation variable \( y \) or the sensor signal \( x \).

**SOLUTION**

Hysteresis compensation:
The company PI has a patent for a reverse piezo model (reference number DE102004019052A1). This model has been expanded with a polynomial to inhibit higher order nonlinearities that cannot be linearized by the reverse piezo model.

**FIGURE 8** Piezo actuator system block diagram

To normalize the transfer behavior to a static amplification of 1 the regulation variable \( y \) will be divided by the quotient \( A \). Thus this factor could be neglected for further considerations. Now being able to feed back the weighted intermediate states \( x_1 \), \( x_2 \) and \( x_3 \) to the system, closed-loop dynamics can be adjusted by the so-called \( k \)-coefficients.

**FIGURE 9** Control structure

The overall control is done by a simple integral action controller to eliminate static and drift distortions and to be able to reach the exact target position. An observer was built to generate the state signals \( x_1 \), \( x_2 \) and \( x_3 \) (observed signals are called \( x_{1b} \), \( x_{2b} \) and \( x_{3b} \)). The Laplace closed-loop transfer function can be described by the following equation:

\[
F(s) = \frac{k_1 \cdot s^3}{s^3 + (1 + k) \cdot s + \left( \frac{2D}{u_0} + T + k \right)}
\]

**FIGURE 10** Closed-loop transfer function

The transfer function shows that all poles of the closed-loop system can be adjusted by the \( k \)-coefficients. Thus a well-damped system can be created without any signal-eliminating filters. The main advantage is that no delays are added to the system. Hence the phase shift between target and real position signal can be minimized. The excitation of the resonance is damped actively even for distortion signals. By choosing an ideal combination of the \( k \)-coefficients (e.g. method of the double relations \( \text{DV}=2 \)), high frequencies (in relation to the closed-loop bandwidth) are damped by the structure with up to -80 dB per decade.
RESULTS OF MEASUREMENTS

Hysteresis compensation:

FIGURE 11 Structural damping of high frequencies

FIGURE 12 Real hysteresis

FIGURE 13 With reverse piezo model

FIGURE 14 With reverse piezo model and polynomial

FIGURE 12 to FIGURE 14 show that the piezo actuator system can be linearized. The result is a nearly constant relation between applied voltage and position. The effect on closed-loop operation is shown below by figures comparing standard PID control with notch filter and the so-called advanced piezo control described in this document. The target was a 100 µm triangle signal with 5 Hz.

FIGURE 15 Tracking error with PID

FIGURE 16 Tracking error with advanced piezo control
The tracking error is reduced to 50%. The position error is constant and the system behaves in the same manner for positive and negative slopes.

Resonant frequency in closed-loop operation:

The distortion signal z is not exciting the resonance. Low frequency parts are damped.

CONCLUSION

The control structure provides not only position control but also damps the system resonance actively. Thus both position control and active damping are provided.

REFERENCES

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