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Improving the Performance of Piezoelectric Inertia Motors

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Abstract:
This paper presents a model based analysis of piezoelectric inertia motors and concepts to improve their performance. Three velocity-optimized movement patterns for the driving body have been derived. The influence of the individual motor parameters on the velocity of the motor is shown and consequences for the design of a high velocity motor are derived. A feed forward control based on the frequency response of the system is introduced and applied to calculate the voltage signal for achieving the desired movement pattern. After discussing the origin of observed distortions of the movement patter, their influence on the motion of the driven body and different methods to reduce these distortions and their effect are addressed.

Keywords: piezoelectric inertia motor, velocity, feed forward control

Introduction

Piezoelectric inertia motors (PIMs) make use of the inertia of a body to drive it by a friction contact in a series of small steps, generally composed of a stick phase and a slip phase between the friction partners. Compared to piezoelectric motors using other drive principles, they have a simple construction and are controlled by a single driving signal, which allows for low production costs and for miniaturization. Originally developed for high precision microscopy applications [1, 2], they are nowadays also used in consumer applications like zoom lenses for cameras in mobile phones [3, 4].

Currently, the design of a PIM is often based on experience and prototyping. This is a time-consuming process, the individual influence of the design parameters is difficult to determine and it is difficult to design a motor that reaches the best possible performance. There are generally two approaches to improve the characteristics of PIMs. One is to improve the construction of the motor, i. e. parameters like piezoelectric actuator configuration, driving and driven body, friction couple and contact force. The other approach is to optimize the electric driving signal of the motor. These two processes are not independent – changing motor parameters will change the optimal driving signal and changing the driving signal will lead to a different set of optimal parameters. In this contribution, we use a model based approach to investigate the influence of the design parameters on the velocity of PIMs and describe a method to determine the voltage signal required to make the piezoelectric actuator move in a desired pattern.

For our fundamental investigations, we have built a prototype motor based on a pre-stressed multilayer actuator, see fig. 1. The actuator has a length of 28 mm and is capable of a stroke of 27 µm. Attached to the piezoelectric actuator, which can be mounted at arbitrary slope angles, is a steel rod. An aluminium slider with exchangeable friction pads and attachable weights moves along the rod. It is pressed against the rod by a variable number of magnets. This construction allows for almost free and generally independent variation of most design parameters.

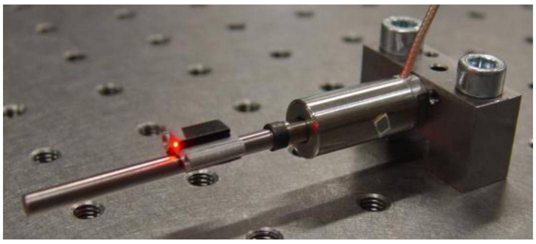

Fig. 1: *Prototype piezoelectric inertia motor*

Influence of Design Parameters

Fig. 2 shows the model we use for our investigations, with the piezoelectric actuator, driving rod m_r and slider m_s. In a first step we aim at optimizing the motor velocity. Assuming excitation by displacement and Coulomb friction with constant coefficients of static and sliding friction, we have derived three fundamental velocity-optimized driving modes for such a motor [5]. They have individual advantages and disadvantages which make them suitable for different applications. In the discrete mode, the slider moves in discrete steps and the mean velocity can easily be controlled. The continuous mode reaches a higher and more constant velocity. The accelerating mode allows the highest velocity but is hard to realize. It will therefore not be investigated any further in this contribution. All three modes reach significantly higher mean velocities than sawtooth-shaped excitation, which is classically used in most inertia motors [5].

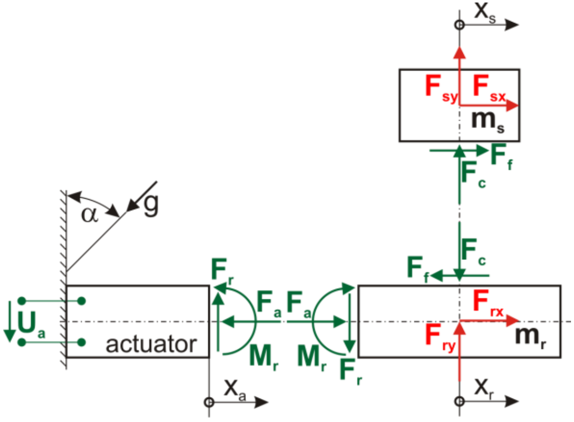

Fig. 2: *Piezoelectric inertia motor model*

We analyzed the model to identify the influence of the design parameters on the mean velocity $\tilde{v}$ of the motor in discrete and continuous mode. It is important to bear in mind that the following results and recommendations only look at $\tilde{v}$ and do not account for other possibly relevant aspects like steadiness of movement or energy consumption. Optimizing these values may lead to very different results. In a final motor, a trade-off between the different targets has to be found.

To be able to analyze a PIM modularly, we use a simplified representation of the *piezoelectric actuator* by two values, the maximum deflection $x_{r,max}$, limited by the free deflection of the actuator, and the maximum possible acceleration $a_{r,max}$, limited by the blocking force of the actuator divided by the inertial mass m_r+m_s (cp. fig. 2). For a given actuator, $x_{r,max}$ and $a_{r,max}$ cannot be varied independently and have to be traded off against each other. We found analytically that $\tilde{v}$ is a function of $\sqrt{x_{r.max}}$ for both drive modes. Increasing $a_{r,max}$ will generally increase $\tilde{v}$. But once a certain acceleration is reached, a further increase will only produce a very slight velocity gain. In the discrete mode, the influence of $a_{r,rmax}$ is generally less distinct than in continuous mode. From a mechanical viewpoint the conclusion is that an actuator with a larger stroke and higher force capability will always lead to a higher velocity. The factors limiting the actuator size will be space, weight and of course cost. The drive electronics also play a crucial role as a higher stroke or force can only be achieved at the cost of a higher demand of voltage or current. The interrelationships between free deflection, blocking force, electrical capacitance and voltage requirement for typical types of piezoelectric actuators are known. This allows to determine the most suitable actuator for a given application and to find the best trade-off between $x_{r,max}$ and $a_{r,max}$.

Generally a *friction contact* with a high coefficient of friction is advantageous for friction driven motors. An analysis of the inertia motor model shows that this is true for the coefficient of static friction μ_s. There is a certain minimal μ_s below which the motor cannot operate as desired. The influence of μ_s is similar in both modes and less distinct for downhill movement of the slider. By increasing μ_s from 0.15 to 1.5, $\tilde{v}$ can be increased by more than 1000% depending on the other design parameters. As long as the motor works in discrete mode, the value of μ_d has no influence on $\tilde{v}$. In continuous mode, $\tilde{v}$ decreases when μ_d is increased, but the influence is far less distinct than that of μ_s. We therefore conclude that a high μ_s is more important for reaching high velocities than a small μ_d. This is true for all slope angles, but especially for uphill operation. Friction coefficients are highly dependent on the operational conditions, especially for the small displacement and high acceleration application in inertia motors. They should therefore not be taken from literature but identified using the actual contact and loads used in the motor. As a high μ_s is a primary goal, rubber is a good candidate.

The influence of a *contact force* acting in addition to gravity is similar for discrete and continuous mode. For uphill and downhill angles above a certain threshold there is a minimal force required for the motor to function properly. If the force is increased further, $\tilde{v}$ also increases, with the effect most distinct for steep uphill operation. A higher contact force also reduces the effect of the slope angle on the slider velocity. It would therefore make sense to use as high a contact force as possible. $a_{r,max}$ defines the maximum possible force above which no sliding can be achieved.

The *mass of the slider* also has a comparable effect in both modes. $\tilde{v}$ is highest for a very small mass and decreases rapidly with increasing mass. At uphill operation $\tilde{v}$ approaches a minimum, at downhill operation it continues decreasing down to zero. At uphill and downhill slopes angles a certain threshold the mass cannot be increased above a certain maximum. It can be concluded that the mass of the slider should be as low as the application allows.

Frequency Response Based Control of the Piezoelectric Actuator

When designing a high velocity PIM it is important that the driving rod shows the correct movement pattern according to the desired drive mode. The rod is moved by a piezoelectric actuator which is usually driven by a voltage controlled source. A constant relationship between voltage and displacement of the piezoelectric actuator can only be assumed for low frequency (quasi-static) operation. If the drive signal contains higher frequencies, the dynamic behaviour of the actuator has to be considered to determine a suitable voltage signal. The characteristics of the voltage source can also be relevant.

The movement patterns for high velocity have high frequency components. Therefore we must consider the dynamic behaviour of the actuator. This could be done be using a closed-loop control, but it would require sensors detecting the rod deflection and make the motor too expensive for many consumer applications. Therefore we propose to use a feed forward control. Using a linear dynamic model covering the first resonance only, no satisfactory control could be achieved [6]. Therefore we have developed a feed forward control based on the frequency response of the system. The process used to determine the voltage signal to drive the piezoelectric actuator is illustrated in fig. 3.

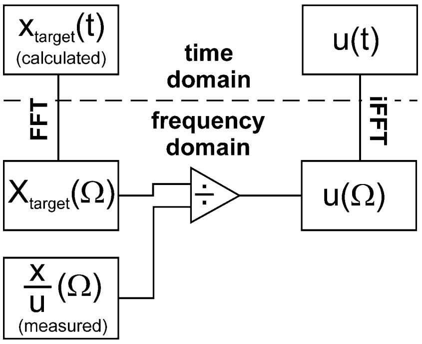

Fig. 3: *Frequency Response Based Control (FRBC)*

The desired motion $x_{target}(t)$ is transformed into the frequency domain. It is then divided by the measured frequency response x/u. This results in the frequency domain representation of the control voltage. It is transformed back into the time domain to get the signal u(t) that is to be fed into the system for achieving $x_{target}(t)$. The system investigated here consists of a power amplifier and the inertia motor described above without the slider. The system input is the voltage u going into the amplifier, the output is the displacement x of the rod. Fig. 4 contains the measured frequency response.

Fig. 5 shows the results achieved for a discrete mode signal at 1 and 10 kHz using a fourier transform with a bandwidth of 160 kHz. The courses of voltage and displacement are very similar at 1 kHz while it seems surprising that the wildly oscillating 10 kHz voltage signal actually leads to the desired motion. There are some superimposed vibrations at low amplitude and the calculated displacement maximum it not reached at 10 kHz.

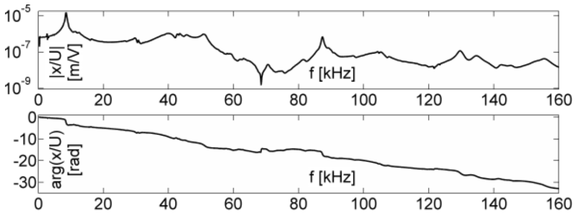

Fig. 4: *Frequency response x/u of investigated motor with amplifier*

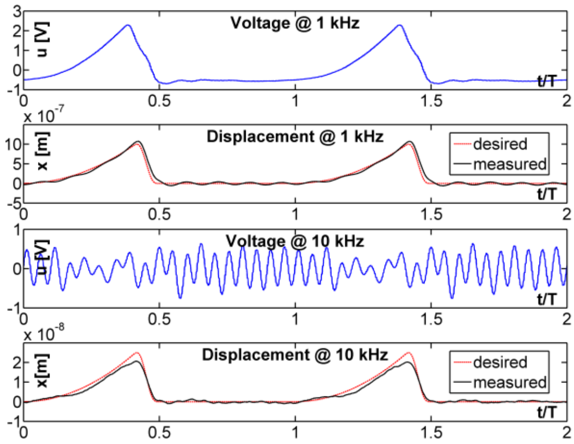

Fig. 5: *Voltage and displacement using FRBC at different frequencies*

The experimental results prove that FRBC works at all investigated frequencies, but also show some unexpected vibrations superimposed to the displacement signal at all frequencies. Slight distortions around the displacement peak were expected at 10 kHz due to the finite resolution of the FFT used for calculating the signal. The other vibrations are unexpected. Their frequencies fit those of peaks in the x/u spectrum of the system shown in fig. 4. For example a vibration at 8.5 kHz is found in the response to the 1 kHz signal and a vibration at 40 kHz in the response to the 10 kHz signal.

These distortions probably result from the nonlinearity of the system under investigation. The characteristics of piezoelectric transducers are not independent of amplitude [7] and the measurements using FRBC were performed at an input voltage significantly lower than the voltage used to identify the frequency response. Additionally, the pre-stressed multilayer actuator under investigation has a relatively complex design which tends to increase nonlinear effects compared to simple transducers.

Effect of Signal Distortions on the Slider Movement

To quantify the influence of these distortions on the movement of the slider, we use a numerical MATLAB/Simulink model of the motor. Switching between static and sliding friction is performed by a Stateflow chart.

The observed vibrations seem relatively small when looking at the displacement, but the oscillation amplitude of the acceleration is significantly higher than the breakaway acceleration defined by the friction contact. Because of this, sliding occurs practically all of the time. This reduces the maximum slider acceleration and therefore the total displacement per step achieved by the motor. The vibrations observed reduce the step size and therefore the effective velocity in the order of 50% and more.

The negative effect of the unwanted vibrations can be reduced by different means. It is preferably to reduce these vibrations as far as possible before additional measures are taken. Reducing the negative effect of the nonlinear, amplitude-dependent behaviour of the piezoelectric actuator is one step into this direction. It could be achieved by measuring the frequency response of the system at different amplitudes and then using the relevant portions of different measurements for calculating the voltage, depending on the amplitudes calculated for the corresponding frequencies from the desired signal.

Another step to ensure proper operation of the motor in spite of vibrations is to lower the desired acceleration of the rod and slider in the phase of stiction. This can be practically realized by assuming μ_s to be lower than its real value when calculating the acceleration of the driving rod in the stiction phase. This will reduce the achievable step size and velocity, but increase the chance that the breakaway acceleration is not exceeded due to unwanted vibrations.

A last step can be to accept the fact that vibrations hinder stiction and change from stick-slip operation to a planned slip-slip operation that uses sliding friction for accelerating the slider. This operational mode has been described in [8]. It is less sensitive to distortions because no transition between static and sliding friction is required. But it can also be shown that the mean velocity can never reach the maximum achievable by stick-slip operation.

Outlook

Before additional measures to reduce the unwanted vibrations or their effects are taken, the effect will be investigated experimentally by measuring the motion of the slider on a rod moving as described above. A test rig to measure the friction force between driving rod and slider is being constructed. These measurements will be used to determine the parameters of a more complex friction model. It must contain the tangential elasticity of the frictional contact which will partly or fully absorb the vibrations of the driving rod. Possibly it is also necessary to include the velocity dependence of sliding friction and the dwell-time or force-rate dependence of static friction [9] in the model.

Conclusions

The influence of various design parameters of a PIM on its velocity have been shown and proves that choosing a suitable set of parameters has a great potential for designing better motors. A feed forward control based on the frequency response of the system has been applied to calculate the voltage signal for achieving the desired movement pattern. This method worked for all investigated signal frequencies. The achieved displacement included some unwanted vibrations. Before this control method can be applied to inertia motors, its quality has to be improved.

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