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Driving concepts for bundled ultrasonic linear motors

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Abstract Several positioning tasks demand translatory drive instead of rotary motion. To achieve drives that are capable, e.g., to drive the sunroof of a car or to lift a car's window, multiple miniaturized motors can be combined. But in this case many other questions arise: The electromechanical behavior of the individual motors differs slightly, the motor characteristics are strongly dependent on the driving parameters and the driven load, many applications need some extra power for special cases like overcoming higher forces periodically. Thus, the bundle of motors has to act well-organized and at last controlled to get an optimized drive that is not oversized and costly.

Keywords Ultrasonic linear motor · High power · Control · Modeling · Characteristics

1 Introduction

Vibration drives are small electrical motors that differ substantially from electromagnetic motors in modus operandi and performance characteristics. These drives work on the following principle: piezoceramics initially transform electrical energy into mechanical vibration, which will be transformed via frictional contact between tip and slider to the desires of motion of the driven part. The impressive simple functional principle provides these drives with a number of favorable properties that make them useful alternatives to classical electrical drives in numerous applications. In addition, linear vibration drives are capable of directly producing translatory movement without the need for gearing. This provides additional advantages over conventional rotary motor transmission solutions, such as high efficiency, less package space, and no backlash.

To achieve drives that are capable, e.g., to drive the sunroof of a car or to lift a car's window, multiple miniaturized motors can be combined. But in this case many other questions arise. The electromechanical behavior of the individual motors differs slightly because of manufacturing and assembly tolerances. The individual motor characteristics are strongly dependent on the driving parameters (frequency, voltage, temperature, prestress, etc.) and the driven load. Many applications, e.g., the drive of a sunroof, need some extra power for special cases like overcoming periodical higher forces (e.g., driving into sealings). Thus, the bundle of motors has to act well-organized and at last controlled to get an optimized drive that is not oversized and costly.

2 Low-cost linear ultrasonic motor

Several ultrasonic linear motors found in literature are base on the use of two different vibration modes, most often a combination of flexural and longitudinal modes, to achieve an elliptic micromotion of surface points, e.g. [1–3].This micromotion is converted to direct linear (or translatory) motion of a driven slider. To gain high amplitudes of the micromotion at moderate input voltages, the ultrasonic vibrator should be driven near the eigenfrequency of its

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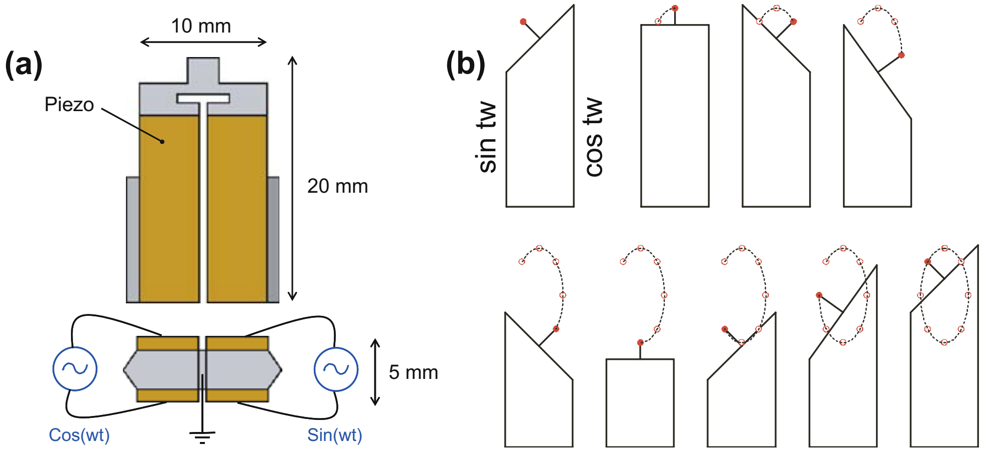


Fig. 1 (**a**) Setup of the ultrasonic vibrator (**b**) excitation of elliptical surface movements by the use of two-phase-shifted longitudinal vibrations

modes. In addition, low mechanical and electrical losses lead to increased efficiency and large amplitude magnification in resonance. This demands a geometrical design that fits the eigenfrequency of two different modes. A frequency deviation of only a few percent leads to unacceptable annoyance of the elliptical motion. Thus, the mechanical design of the vibrators has to be done very carefully, especially as manufacturing tolerances of low-cost products are worse as needed. Other causes for frequency deviation of different modes might result from nonlinearities, such as the intermittent contact mechanism of vibrator and driven part and material nonlinearities. Hereby it is rather complicated to adjust the driving parameters of bimodal ultrasonic motors to an optimum state.

To get a more broadband and less sensitive motor, a vibrator using twofold the same longitudinal vibration mode has been developed. It is driven with two time-shifted phases to achieve an elliptical movement [see Fig. 1(a)] [4].

The vibrator consists of four equal piezoceramic plates that are bonded to a substrate made of brass. In between the piezoceramics a driving tip made of aluminum oxide is attached to the substrate. Each two of the piezoceramic plates build one driving system. The systems are supplied with an AC voltage of same frequency and amplitude, but different in phase. The operating principle is shown in Fig. 1(b). The 90° phase shifting up and down movement of the legs leads to the desired elliptical motion of the driving tip, which will be transformed through frictional contact between the moving tip and a slider pressed to the desired motion.

3 Driving concepts and control strategy

The control strategy for a bundle of miniaturized low-cost motors has to fulfill at least three tasks: control the single motor, coordinate the bundle of motors, and adjust driving parameters of the bundle in such a way as the positioning demands are satisfied.

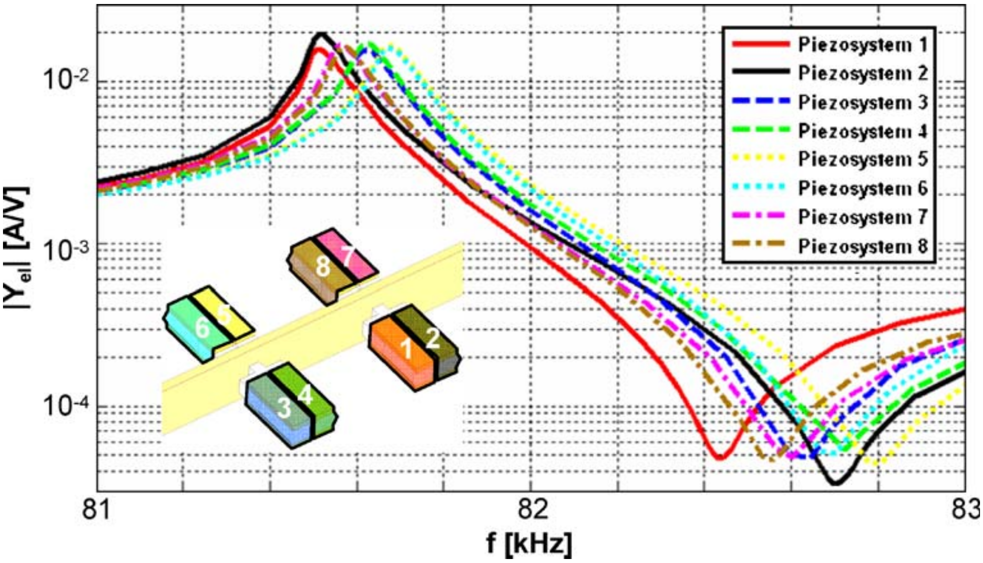
3.1 Control of a single motor

Typically the electromechanical state is influenced strongly by external parameters like varying operation conditions, wear, aging, or temperature. In literature one can find control strategies for adjusting the parameters for operating one piezosystem of the motor in an optimum state [5]. Whereas a model-based analysis indicates whether driving parameters like frequency, input power, and normal force have to be adjusted to achieve the desired motor characteristics of the single drive. For deriving the actual model parameters, the control of a single motor includes an online measurement of its electromechanical state, which can be calculated from the systems frequency response. The frequency response of a system can be measured online by applying an impulse or alternatively white noise to the system and measuring its response in the frequency range or sweeping a constant-amplitude signal through the bandwidth of interest and measuring the output level. Once the model's parameters are identified, the motor's driving parameters can be controlled in such a way as the desired motor characteristics are reached in an optimum manner. Online parameter identification will be needed to guarantee best performance all over lifetime.

3.2 Bundle coordination

Generally, thrust of single motors should simply add up to the total thrust of the drive and no load velocity should be the same for single motors and total drive. But because of interference or even helpful synergetic effects in the driven part, the composition of the overall characteristics is somewhat more sophisticated and thus needs a modeling (see [6]). The criteria for evaluating the driving concepts will be robustness, efficiency, power, complexity, and hardware costs. In Fig. 2 the measured frequency responses of four motors of the same type with their respective eight piezosystems are depicted.

Fig. 2 Electrical frequency responses of all four piezomotors



The resonance frequencies of the two vibration systems of each motor differ only by some few hertz among each other and all the motors lie in a frequency range of about 150 Hz. Compared to other type of piezoelectric motors this is a very small bandwidth and can be explained with the simple structure of the motor. Based on the considerations for driving a single motor we evolved four different driving strategies for a set of motors (see Fig. 3):

(1) "Individual excitation": Every vibration system will be excited by its own resonance frequency.

(2) "Single resonant excitation": All motors will be driven at a single excitation frequency within the resonance area of all motors. We suggest as an advantageous frequency the maximum of the graphical summation of all frequency responses.

(3) "Sweep": A bandwidth in the resonance area of all motors will be defined and the excitation signal will be swept up and down in frequency.

(4) "Single nonresonant excitation": Equal to the single resonant excitation but in this case the excitation frequency will be chosen in the nonresonant area of all

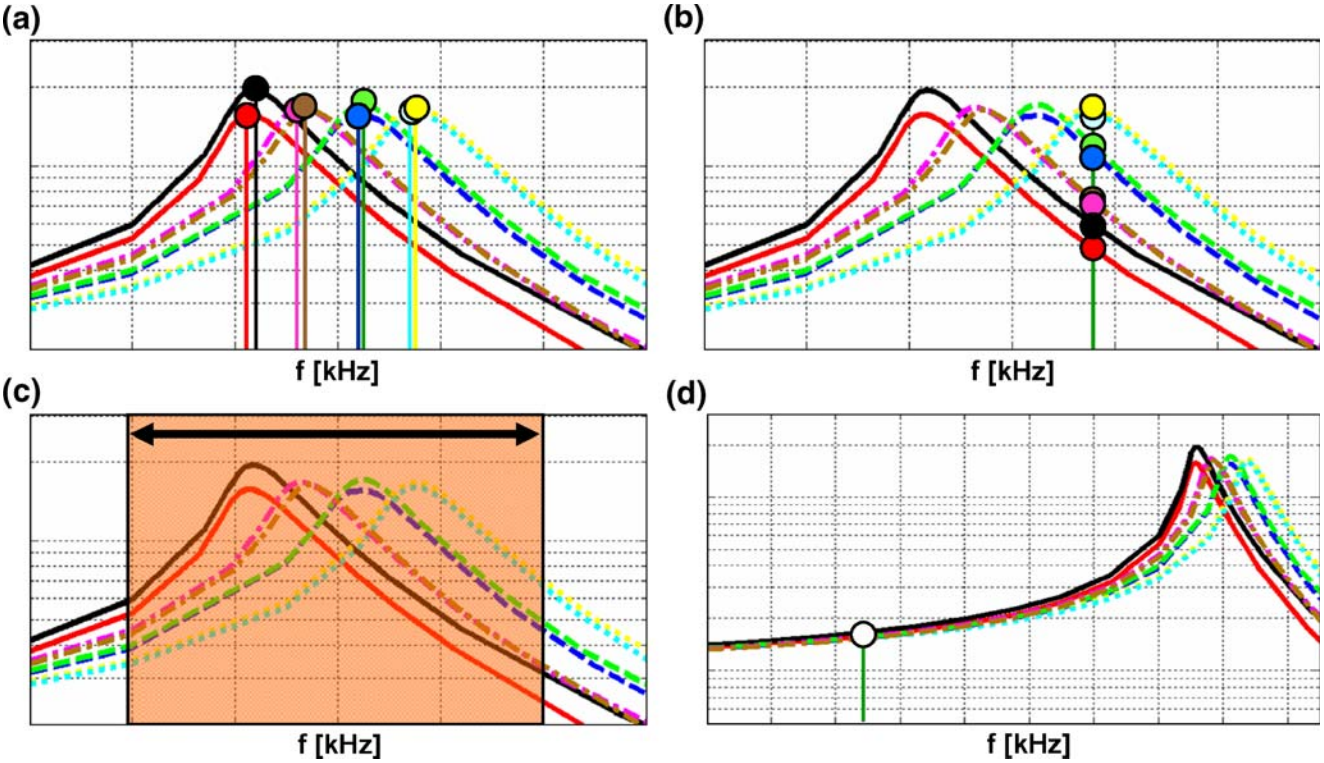


Fig. 3 Driving strategies

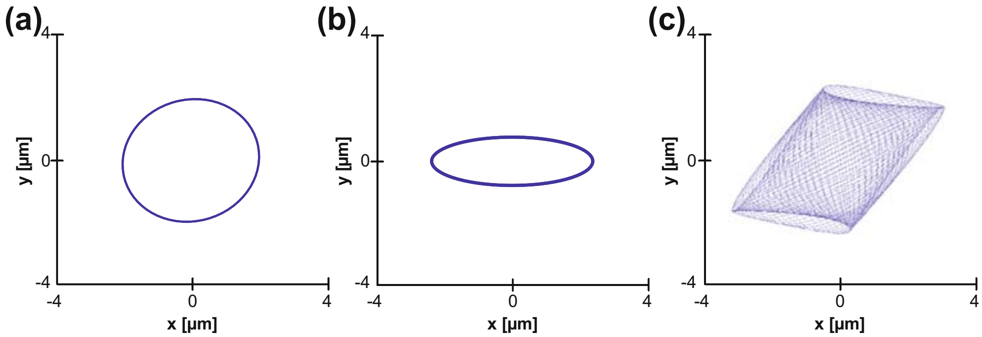


Fig. 4 Operation scenarios for an (**a**) ideal and (**b**, **c**) real motor

frequency responses. In the next section the benefits and drawbacks of these strategies will be discussed.

4 Modeling

There are many different models that can be used within the development of a piezoelectric motor. Whereas sophisticated physical models and detailed finite element method models are used during the design of the motors, much simpler models are more appropriate for control. As long as the motors are driven close to resonance, typical analogous circuits can be deployed to model their electromechanical transfer behavior. Models for single-phase-driven piezoelectric elements are well known (e.g., [7]).

4.1 Model of a single motor

The model for the piezoelectric motor must contain three main operational functions: generation of vibration via the piezoelectric effect, combining vibrations to achieve an elliptical trajectory, and transformation of vibrations into macroscopic linear movement of a driven part. For simplicity, within this contribution each block of this structure is filled with very simple models [8]: the twofold used model for a basic piezoelectric vibrator, the kinematics used within the motor, and the contact model. Electric quantities are included via the analogy of force and voltage and velocity and current. Much more detailed ones do exist, but first, experimental validation of the overall structure will have to show how to detail one or the other component. The advantage of a module-based modeling lies in the way parameters can be identified that can be done easily step by step. The elementary kinematic model includes geometric transformation only, but it can be extended by terms of inertia, damping, and compliance. The output of that sub-model, a vector of forces and velocities at the driving point, is used directly as the input for the mechanical contact model. The simplest model for the contact of vibrator and driven part is the rigid one-point contact.

Additional input parameters for this model are the friction coefficient µ between motor tip and slider, the rigidity of the support, the dynamic properties of the slider (as damping characters and weight), and the preloading normal force acting between vibrator and driven part. The contact model directly outputs the motor characteristics thrust and velocity. Other characteristics like efficiency can be calculated by including data from the basic piezoelectric models. More sophisticated models are already known and should be investigated, if experimental validation shows its necessity (see [9]). The complete motor model was implemented in Matlab–Simulink. With this model we calculated the trajectories of the driving tip for different excitation frequencies (f_1, f_2) and resonance frequencies (f_{r1}, f_{r2}) (see Fig. 4).

Table 1 Driving concepts evaluation.

	Individual excitation	Single nonresonant excitation frequency	Single resonant excitation frequency	Sweep
ΣP_{eff} [W]	0.1328	0.0015	0.0638	<0.0638
Efficiency	–	– –	+	O
Complexity	– –	+ +	+	+
Robustness	–	+	+	+ +
Hardware costs	– –	+ +	+	O
Comment	Different velocities interference → beat		Different velocities	Different velocities

The “ideal” motor is an imaginary drive with identical electromechanical behavior of each piezosystem ($f_{r1} = f_{r2}$), which will be excited at its resonance frequency [see Fig. 4(a)]. The simulation result is an elliptic trajectory, with which a slide can be driven frictionally. For the “real” drive we identified the model parameters for each piezosystem from one prototype experimentally, whereas the values for the two piezosystems differ slightly because of manufacturing and assembly tolerances ($f_{r1} \neq f_{r2}$). With this data we simulated the cases of an individual excitation for each piezosystem at its resonance frequency and an excitation at a single frequency. Figure 4(b) shows the trajectory of a phase-shifted excitation at a single frequency. An excitation of the two-piezosystem at each resonance frequency leads into an unfavorable interference of the oscillations at the driving tip [Fig. 4(c)]. The needed elliptical trajectory rotates in it self with the beat frequency, which means that the trajectory changes its rotating direction once in one cycle and the driving characteristics is reduced significantly.

4.2 Model for a motor bundle

For modeling the motor bundle we cloned the motor model of the single motor and assembled them to a model for the collective propulsion of one slide. In the following step we identified model parameters of four piezomotors experimentally, implemented the four driving strategies, and evaluated the results. As an experimental criterion the effective power P_{eff} was calculated from the measured frequency responses of all piezosystems from the admittance and phase between input voltage (U_{in}=1 V) and output current (see Table 1).

An individual excitation for all piezosystems results into the same problem as for a single motor. Every piezosystem is driven in its optimum state, but the needed power transfer from oscillation energy into thrust is not possible through interference and beat and lowers the efficiency of power transformation significantly. Furthermore, this excitation strategy would require at least eight independent excitation systems, which would make the setup very expensive and complicated in controlling. In contrast to this strategy, an excitation at a single frequency in the nonresonant area would be very uncomplex and stable, but also very ineffective. Hence, an excitation at a single frequency in the resonant area could be considered whereby the problems of the two previous strategies would be attenuated. The motors will be driven very near to their resonance frequencies, but with the consequence that no beat occurs. Exciting all motors at a single frequency, a problem could arise with different driving velocities of the motors, which could be solved by amplitude balancing through variable exciting voltages. This challenge also has to be met in the sweep strategy. This kind of excitation is very robust because the controller covers the whole interesting bandwidth and is independent from fast deviations of the driving parameters like varying resonance frequencies or damping. The bandwidth of the swept range has to be chosen very carefully because a too wide area would cause a reduction in efficiency, whereas a too small spectrum would cause a loss of robustness. All these consideration that are made for a two-phase single motor can be adapted to a set of single-phase motors very easily with the difference that no unfavorable beat occurs.

5 Conclusions and outlook

The main reason for the limited range of applications of piezoelectric linear motors is their small force and power range. One step to achieve drives with higher power may be the approach of bundling multiple miniaturized motors. This attempt raises some demands in matters of modeling and control to obtain an optimized drive that is not oversized and costly. We introduced different driving strategies for a single motor as well as a motor bundle. We evaluated these strategies with a simple modular model that includes effects of parameter deviation and load dependency of single motor’s characteristics as well as interaction of a multiple of drives on one driven part. The next step in our approach of parametric based control will be the experimental identification of parameters that affect the systems performance. The simulation models will be compared and adjusted with the help of these experimental examinations. Finally, a set of motors consisting of a mathematical model for the complete system can be configured automatically.

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