Properties of a Piezoelectric Travelling Wave Motor Generating Direct Linear Motion

Eigenschaften eines piezoelektrischen Wanderwellenmotors als Lineardirektantrieb

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Beitrag zur

Actuator 98

17. - 19. Juni 1998

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Institut für Konstruktion und Fertigung in der Feinwerktechnik

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PROPERTIES OF A PIEZOELECTRIC TRAVELLING WAVE MOTOR GENERATING DIRECT LINEAR MOTION

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Abstract
Piezoelectric travelling wave motors are well known as rotatory drives. Building up a linear direct drive, which makes use of the travelling wave principle needs a travelling wave to be excited on a linear stator. The existence of orthogonal mode shapes as a prerequisite for the generation of a travelling wave is to be proved for a ring type stator with two linear portions. Mechanical and electrical properties of the stator as well as operating characteristics of the linear direct drive measured on a prototype are presented.

Introduction

In the past years rotatory travelling wave motors have been developed, displaying particular properties like high torque per volume, small start-stop time-constants, high positioning accuracy and high holding torque with no current applied [1].
However, the purpose of many drive applications is linear motion and it is aimed to take advantage of the principle of the travelling wave motor for generating direct linear motion.
In a paper published at Actuator 96, such a piezoelectric ultrasonic linear drive has been presented with focus on a basic understanding of the operation principles and on the results of finite element analysis [2]. An advanced prototype based on these results has now been tested, and it is proved that implementation of this motor is possible.

Design of the motor

Excitation of a travelling wave by superimposing two standing waves, as it is done in the rotatory motors, can be applied to linear direct drives too.

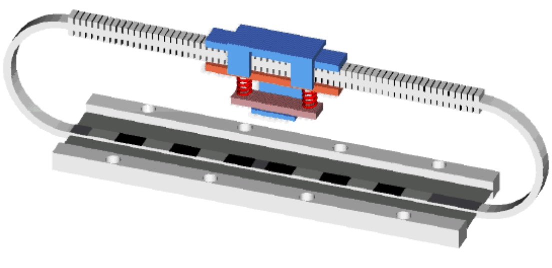

Fig. 1: Linear travelling wave motor with ring-type stator

This requires the travelling wave to propagate on a closed ring-type stator. There are linear portions within the ring for directly taking off linear motion by a slider. The design shown in Fig. 1 allows the slider to be pressed to the upper straight portion from two sides to increase the force transmitted by friction and to prevent introducing any deformation by the applied contact forces. A comb-tooth structure increases the motion in the driving direction. Piezo elements are attached to the lower straight portion to excite the necessary travelling wave. The stator ring is suspended by two membranes along both sides of the lower straight portion. Fixing the stator rigidly would not allow any travelling wave to develop.
As no other forces than in the driving direction should be applied to the slider, load is not mounted directly to the slider but to a linear ball track which is connected to the slider by membranes (see Fig. 2).

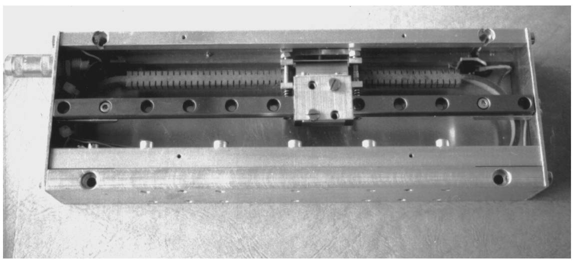

Fig. 2: Investigated prototype

Excitation of a travelling wave in the stator

The excitation of the travelling wave is done by superimposing two standing waves, which correspond to a pair of orthogonal modes. Therefore, two separate assemblies of six alternately polarised piezoceramic elements exist. Each assembly is placed on the stator ring in a way to optimally excite one of the mode shapes, i.e. with a quarter wave length between the two assemblies because of the orthogonality of the modes. The assemblies are loaded electrically by two voltages which are 90° out of phase and of magnitude 80 V.
A pure travelling wave can only be excited if both orthogonal mode shapes possess the same

resonance frequency. Such degenerated mode shapes can be achieved by varying geometry, e.g. changing the ratio of the radius of curvature to the length of the straight portion. By that the modal mass and modal stiffness become equal for both modes, yielding the same resonance frequency. A FEM analysis can be done to show whether an acceptable travelling wave can be excited for a particular design, taking into account all influences mentioned in [3]. This is accomplished for modes No. 97 and 98 at 51 kHz, which are a pair of orthogonal bending mode shapes, with the stator made of aluminium, a length of the straight portion of 170 mm and a radius of curvature of 25 mm. The calculated resonance frequencies differ only by approximately 0.006%.

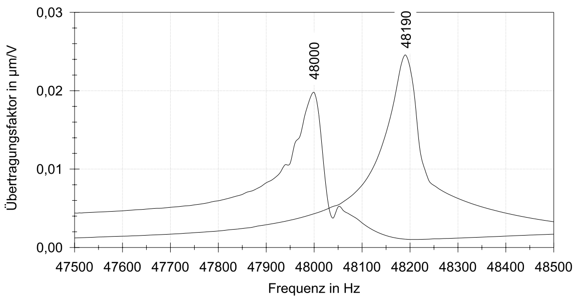

Fig. 3: Measured frequency responses of the two modes used for the prototype

However, as shown in Fig. 3, the prototype's geometry and the properties of the piezo elements from the supposed values lead to modes that do not degenerate. The measured resonance frequencies differ by 0.40%. Hence, a frequency between the measured resonance frequencies of the two modes is used for the prototype.

Trajectories of stator points

Simulating the forced vibration of the ring-type stator shows whether a pure travelling wave is excited or some standing wave component exists. The conditions under which a pure travelling wave occurs are mentioned in [4]. In the case of a pure travelling wave all points on the interfacing surface to the slider move on identical elliptical trajectories. However, if the orthogonal modes used do not degenerate, the difference in resonance frequency accounts for disturbing the excitation of a pure travelling wave. The major axises of the ellipses are varying in length and inclination for different points because of a different frequency response in gain and phase of the two mode shapes. Other influences on the excitation of a travelling wave are unintendedly excited modes that exist close to the used pair of bending mode shapes.

Fig. 4 displays the simulated trajectories of steady state motion for points located at a height equal the bottom of the grooves on the upper straight portion. The x-position counts from the left edge of the comb-teeth and extends over one wave length.

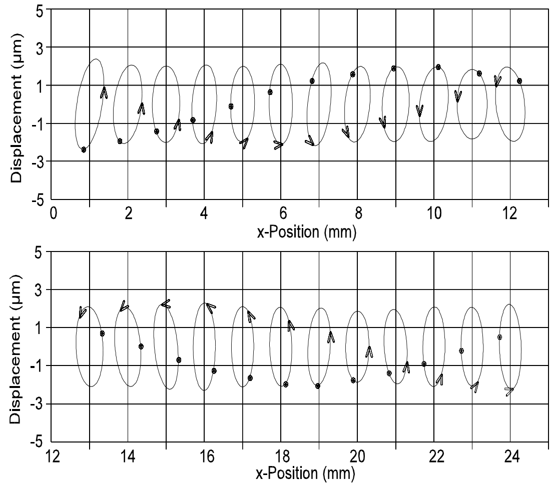

Fig. 4: Simulated trajectories of points located on bottom of grooves (f = 51001,3 Hz)

Disregarding small irregularities in the length of the major axis and inclination of the ellipses, an almost pure travelling wave is achieved.
As the modes do not degenerate for the prototype's stator, greater irregularities can be expected. Fig. 5 displays the corresponding measured trajectories at a height equal the bottom of the grooves, which are still about the same size as the simulated ones.

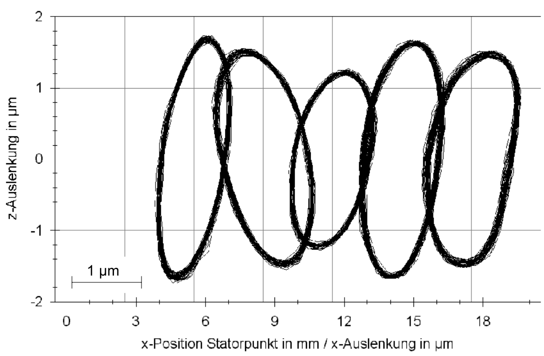

Fig. 5: Measured trajectories of points located on bottom of grooves (f = 48100 Hz)

The motion transmitted to a slider is determined by the trajectories of points in the interfacing surfaces on top of the teeth. Fig. 6 displays the simulated ellipses for the according surface points to Fig. 4. The displacements in x-direction become approximately as big as the transverse displacement (z-direction). This shows that the comb-teeth fulfill their task to scale up the motional quantity in the driving direction. The irregular deformation of the teeth themselves accounts for the ellipses being different to each other.

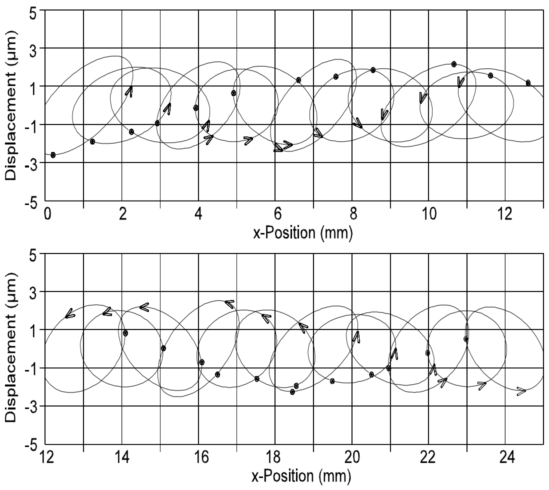

Fig. 6: Simulated trajectories of points located on top of the teeth (f = 51001,3 Hz)

Fig. 7 shows the measured trajectories for points at a height in the middle between the grooves and the surface. Due to the optical method of measurement used, measurement of the trajectories of points on the surface was not possible.

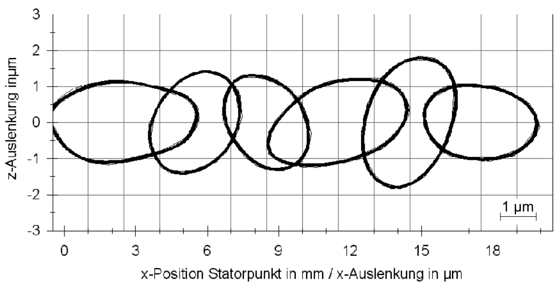

Fig. 7: Measured trajectories at a height in the middle between the grooves and the surface (f = 48100 Hz)

Motor characteristics

Testing the motor's abilities, a very stable behaviour could be observed for all characteristics: acceleration, velocity, time constants, propelling force and efficiency. No wear or fatigue was observed so far. The motor accelerates with up to 60 m/s² and reaches velocities over 0,6 m/s. The drive's propelling force stronly depends on the compressive force between the slider and the stator. Characteristic curves of velocity versus propelling force for different compressive forces between the slider and the stator are shown in Fig 8.

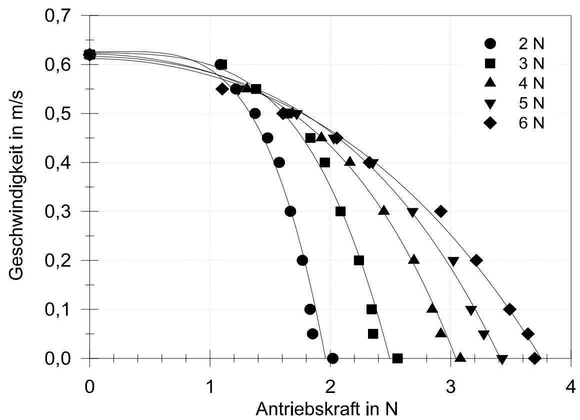

Fig. 8: Characteristic curves of velocity versus propelling force, depending on the compressive force between slider and stator ring

The dynamic behaviour of the new linear motor when used for positioning purposes in a closed control loop has not been thoroughly tested yet. However, the behaviour at acceleration and deceleration has been inverstigated in detail.

As shown in Fig 9, the slider's velocity is approximately proportional to the voltage exciting the travelling wave, but the acceleration remains constant. Thus, the time constants are shorter when a lower velocity is set.

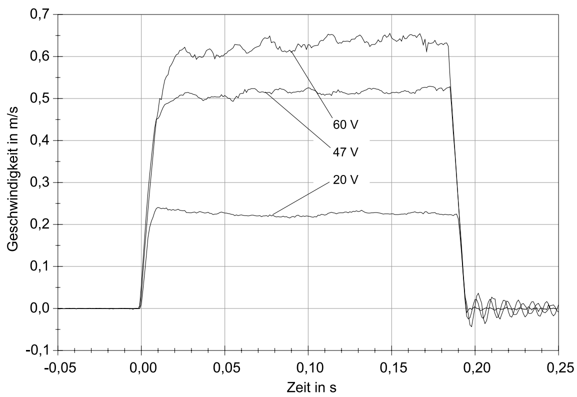

Fig. 9: Velocity versus time, depending on the exciting voltage output

The maximum time constants for the motor running under a mass load of 100 g attached to the slider are 34 ms (start) respectively 30 ms (stop). Running idle, the constants are 10.5 ms (start) and 10.3 ms (stop).

The corresponding curves of the velocity versus time are shown in Fig 10.

Severe oscillations can be observed when the motor stops. This is because of the stator being mounted on its lower straight portion, while the force of the decelerating mass acts on the upper portion, causing the stator to oscillate with a low frequency. Therefore, future prototypes will be mounted on short membranes at the ends of the upper straight portion, which will lead to a much stiffer structure.

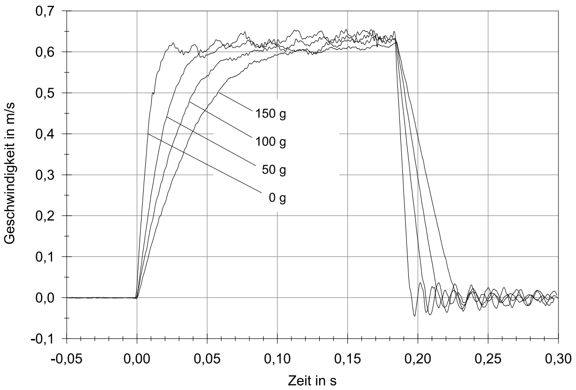

Fig. 10: Velocity versus time, depending on the mass load attached to the slider

To investigate the connection between the stator's oscillations and the slide's movement and to determine the motor's response time when starting the motor, a measurement with great time resolution has been carried out. As shown in Fig 11, the response time of 0.35 ms is correlated with the second increase of the amplitude of the stator's oscillations, which occurs when both waves excited by the two assemblies of piezo elements superimpose and a travelling wave develops. After only 1 ms the travelling wave has grown to its maximum.

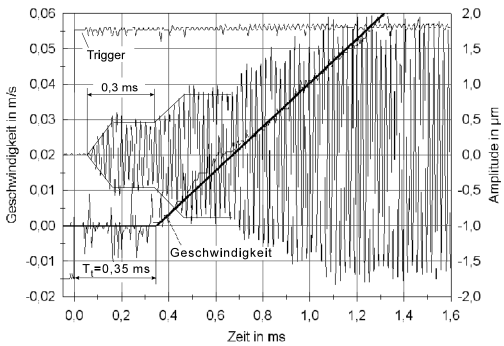

Fig. 11: Correlation between the stator's oscillations and the slider's acceleration

Considering the fact that a travelling wave motor remains in its position at maximum torque or force with no current applied, its efficiency is not as important as for DC motors. However, it is still a point of major interest.
The mechanical output can be calculated from the curves of the propelling force versus velocity. The electrical input was measured at the power supply of the electronic circuit, which means that the efficiency shown in Fig. 12 is a total efficiency of the motor and the circuit. More detailed informations on this can be found in [3].

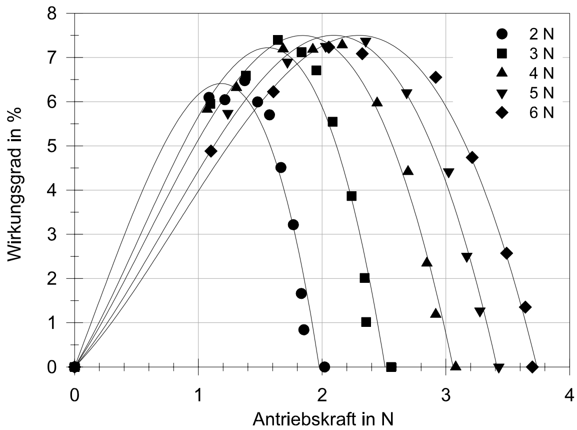

Fig. 12: Efficiency versus propelling force, depending on the compressive force between the slider and the stator

Conclusion

It has been shown that it is possible to excite a travelling wave in the ring-type stator of the proposed design of a linear direct drive which can achieve reasonable good characteristics. Strong points are short time constants, high velocity and an accelaration which is independent of the set velocity. Currently work is focused on improving the performance of the motor, especially efficiency and maximum propelling force, and on new concepts for the electronic circuit.

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