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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 are calculated by means of a finite element analysis including electromechanical coupling effects. The system behaviour can be investigated in this way to a much deeper extend as it is possible by taking measurements on prototypes.

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. Such motors have found already applications in mass-products, e.g. autofocus systems of cameras.
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 such direct linear motion.

Possible designs of linear travelling wave motors

There are different known solutions to build up a linear travelling wave drive. For example the linear motion could simply be achieved by pressing a linear rod tangentially onto the stator of a rotatory motor, Fig. 1. The drawback of such an assembly is that the range of motion is determined by the length of the rod, implying to move large mass. Additionally, forces acting in the transverse direction to the direction of motion tend to excite vibrations in the audible range, which need to be prevented or absorbed by any means.

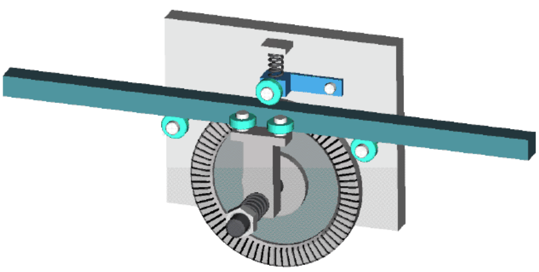

Fig. 1: Linear travelling wave drive with a straight rod pressed tangentially onto rotational symmetric stator

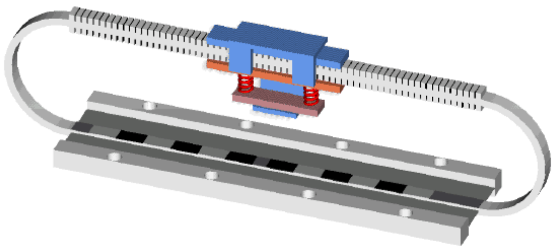

Fig. 2: Linear travelling wave motor with ring-type stator

A second approach is reported in reference [1], where it is tried to excite a travelling wave on a finite rod. This can be achieved by using two similar Langevin transducers, one to excite a propagating wave nearby the one end of the rod and a second one for absorption when it arrives at the other end. The absorbing transducer needs to be electrically wired in an appropriate manner. By switching the circuits connected to the transducers the moving directing can be changed. However, there is no way to take advantage of resonance phenomena because the superimposition of several wavetrains has to be avoided. Therefore, high power transducers of big size are used to achieve the necessary wave amplitudes.
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. 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 suggested design shown in Fig. 2 allows the slider to contact the upper straight portion from two sides to increase the transmitted force and to prevent introducing any deformation by the applied contact forces. A comb-tooth structure increases the motion in

the driving direction. 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.
Building up such a linear direct drive requires the determination of resonance frequencies and mode shapes. This will be described in the subsequent sections.

Investigation of a linear travelling wave motor using a ring-type stator

To realize a linear travelling wave motor with a ring-type stator, the existence of orthogonal mode shapes has to be proved. Because of the complicated geometry of the design in Fig. 2 the finite element method (FEM) is applied. Including the piezoelectricity in a coupled field analysis the electromechanical properties can be determined additionally.

Modal analysis

The alternately polarised piezoceramic elements mounted onto the inner face of the lower straight portion are modelled as active material. Applying an electrical load of 0 V to both electrodes of all piezoceramic elements yields the series-resonant frequencies being computed, particularly since no damping is considered. As mechanical boundary conditions, all nodes on the outer edges of the membranes are hold fixed.
Fig. 3 shows a typical bending mode shape of the ring-type stator. The results of the modal analysis reveal that orthogonal mode shapes exist for the ring-type stator, Fig. 4. The mode shape no. 98 is symmetrical to the vertical centre line, whereas the mode shape no. 97 reveals point symmetry if irregularities due to the piezoceramics, the membranes and the comb-tooth structure are disregarded.
However, the pairs of bending mode shapes do not necessarily degenerate as they always do for

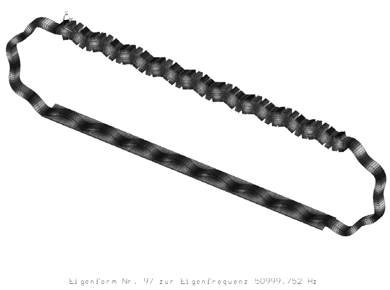

Fig. 3: Bending mode shape of ring-type stator

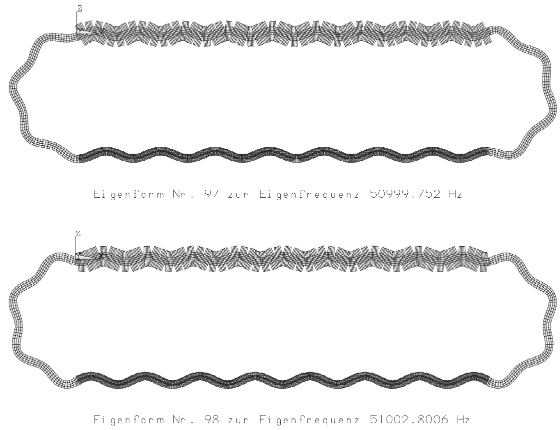

Fig. 4: Pair of orthogonal bending mode shapes

rotationally symmetric stators. A pure travelling wave can only be excited if both orthogonal mode shapes possess the same resonance frequency. 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. The mode shapes of Fig. 4 are such a degenerated pair with numerically calculated resonance frequencies differing only by approximately 0.006%.

Electromechanical coupling coefficient

As mentioned earlier the electromechanical properties can be investigated by a coupled field analysis. The effective electromechanical coupling coefficient gives a figure of merit for the electromechanical energy conversion. It is defined by the equation:

$$k_{eff} = \sqrt{\frac{f_p^2 - f_s^2}{f_p^2}} \qquad \textbf{(1)}$$

Due to equation (1) the parallel-resonant frequencies f_p have to be determined besides the series-resonant frequencies f_s already calculated in the last section. This requires a second modal analysis with different electrical conditions. All electrodes of the piezoceramic elements of the interface to the metal ring are set to a potential

	f_s in Hz	f_p in Hz	k_{eff} in %
mode no. 97	50999,75	51037,91	3,87
mode no. 98	51002,80	51043,49	3,99

Tab. 1: Electromechanical coupling coefficients

of 0 V and all other electrodes are floating. For that charges generated in the piezoceramic elements cannot equalize anymore. Table 1 gives a summary of calculated frequencies and coupling coefficients.

Excitation of a travelling wave in the ring-type stator

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 [2]. 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. For example a longitudinal mode shape with a resonance frequency close to the bending modes causes similar variations of trajectories described above.

For designing a ring-type stator choosing the radius of curvature is an important question. Since the only necessity of the ring shape is to guide the travelling wave, a radius as small as possible is desirable to be able to build a small drive. However, the radius of curvature cannot be made unrestrictedly small because bending stiffness changes with a smaller radius. The distribution of bending stress becomes hyperbolic across the section and the neutral plane moves towards the centre of curvature. This results in discontinuities at the junctions between the straight and curved portions of the stator at which reflections of the travelling wave might occur and thus a pure travelling wave cannot be achieved. A scattering analysis can be performed to investigate the influence of the radius of curvature on reflection. This analysing technique is known from microwaves and has been applied to mechanical systems for large space structures in [3]. Using the coupled differential equations given in [4] to describe the wave propagation in the curved portions, a transmission coefficient for a travelling wave passing over from the straight portion into the curved portion can be calculated as shown in Fig. 5. Geometry and materials are same as in the FEM calculations. The magnitude

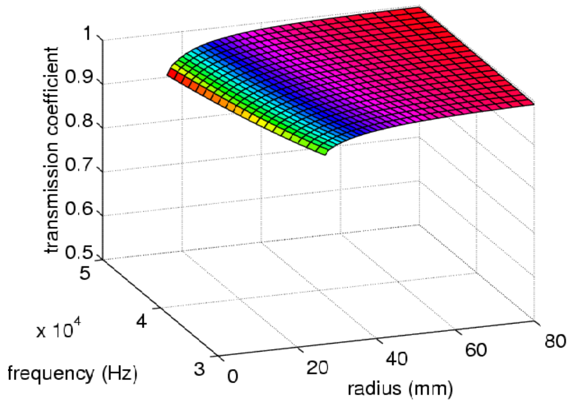

Fig. 5: Transmission of bending travelling wave into curved portions (magnitudes only)

of the transmission coefficient becomes already less than unity for radii between 40 to 60 mm. This means that a travelling bending wave gets reflected to a certain amount. For higher frequencies smaller radii can be realized without reflection taking place. The border marked by the left edge of the surface in Fig. 5 displays the radii for which the curved portion of the stator possesses a cutoff frequency of the longitudinal mode. Due to the existing coupling between bending and longitudinal waves, things become more severe below this line and a pure travelling bending wave cannot be excited. The influence of any existing reflection for combinations of frequency and radius beyond the border depends on the mechanical damping of the system.

A FEM analysis can be done to show whether an acceptable travelling wave can be excited for a particular design, taking into account all mentioned influences. This is accomplished for the pair of orthogonal mode shapes given in Fig. 4; with the stator made of aluminium, a length of the straight portion of 170 mm and a radius of curvature of 25 mm.

The excitation of the travelling wave is done by superimposing two standing waves, which correspond to the 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. That means the changes in the polarization direction are placed in the vibrational nodes of each mode shape, requiring an additional passive piezoelectric element of 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. Fig. 6 displays the trajectories of steady state motion for points located at a

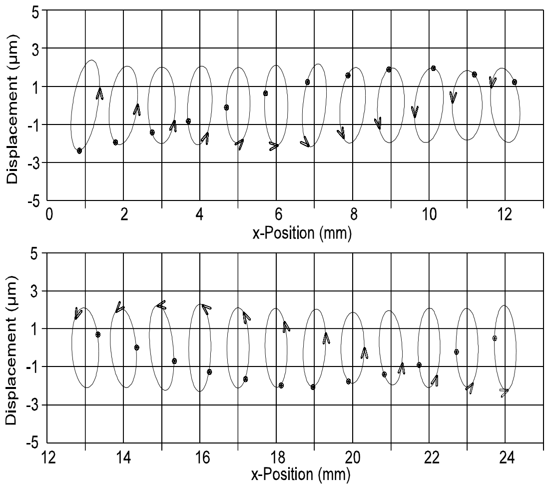

Fig. 6: Trajectories of points located on bottom of grooves (f = 51001,3 Hz)

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.

Disregarding very small irregularities in the length of the major axis and inclination of the ellipses, an almost pure travelling wave is achieved. Since the used orthogonal mode shape are degenerated the irregularities can only result of reflections or any unwanted mode being excited. The latter is true since a very small quantity of a longitudinal mode can be determined by investigating displacements in the neutral plane.

The motion transmitted to a slider is determined by the trajectories of points in the interfacing surfaces on top of the teeth. Fig. 7 displays the ellipses for the according surface points to Fig. 6. The displacements in x-direction become approximately as big as the transverse displacement (z-direction). This shows that the comb-teeth fulfill

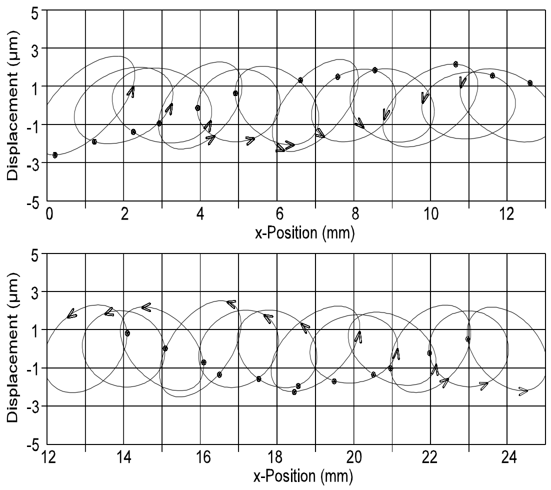

Fig. 7: Trajectories of points located on top of the teeth (f = 51001,3 Hz)

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.

Frequency response analysis

An additional frequency response analysis reveals the frequency dependance of mechanical and electromechanical properties of the system. For example the resonance curve of the travelling wave (Fig 8), supplied current and power, etc. can be computed.

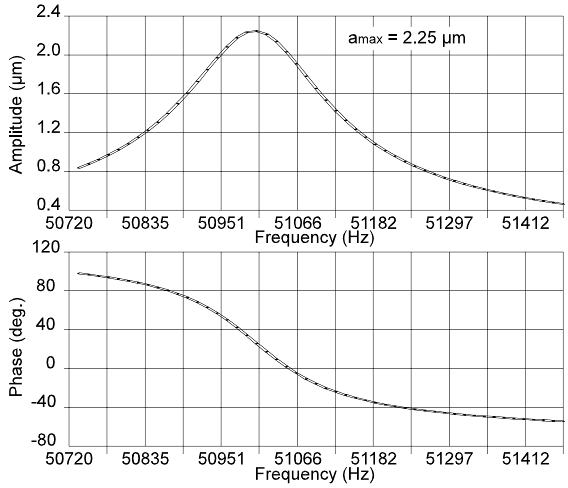

Fig. 8: Resonance curve of the travelling wave (electrically excited by 80 V)

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. Some prototypes have already been built up and tested. Currently work is focused on improving the performance of the motor.

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