Piezoelectric Linear Drives

Wim Van de Vijver¹, Steven Devos², Hendrik Van Brussel¹, Dominiek Reynaerts¹
¹ Div. Production Engineering, Machine Design and Automation, Department of Mechanical Engineering, Katholieke Universiteit Leuven, Leuven, BELGIUM
² Flanders’ Mechatronics Technology Centre, Leuven, BELGIUM

Abstract: The objective of the presented research is the development of an accurate and at the same time rigid positioning system. This research presents a new concept of positioning stage preserving the stiffness through the integration of bearing, transmission and drive functions into a multi-DOF positioning system. Piezoelectric actuators combine a high position resolution with a high passive stiffness and a highly dynamic performance, making them appropriate for the application in the proposed positioning system. A drive module has been built that can provide a stepping motion for accurate positioning while a resonant operation mode provides a high drive speed. This paper will present some design characteristics of the drive modules. In addition, the paper presents the design of a linear positioning system integrating the drive modules.

Keywords: ultrasonic motor, positioning system, resonant

1 Introduction

Throughout the industrial world there’s a growing need for positioning systems with a high accuracy and a high stiffness. Current developments in advanced measurement systems and machine tools require positioning systems that combine high stiffness with a high positioning accuracy. Moreover, in order to reduce machining time, a high positioning speed is favorable. Current solutions of multi-DOF positioning systems are often based on a stacked construction of linear systems consisting of an electromechanical drive, a transmission and a linear guiding system. Due to the series connection of components this configuration diminishes the resulting stiffness and leads to an accumulation of errors. Therefore, research is focussed on overcoming these drawbacks. A concept of positioning system is sought for that preserves the stiffness of the system through the integration of bearing, transmission and drive system into a multi-DOF positioning system. Piezoelectric actuators combine a high position resolution with a high passive stiffness and a highly dynamic performance, making them appropriate for
the application in the proposed positioning system[1]. Our research group has developed and tested several novel concepts of positioning systems [2].

A stage that is able to move along the three in-plane directions and to make small correction movements in the out-of-plane directions has been successfully tested [3], [4]. This positioning system combines an accurate, smooth motion with a very high stiffness and a high positioning stroke. However, due to the complicated drive signals, drive speed is limited. A piezoelectrically driven travelling wave XY-stage is another developed concept resulting in a positioning stage integrating the driving, bearing and transmission function [5]. The main disadvantage of the proposed drives is the low speed.

This paper presents the concept of a modular positioning system built-up with drive modules that combine two operation modes: a stepping mode providing a slow but extremely accurate positioning and a resonant operation mode providing a high drive speed. The design of two drive modules are presented here: a linear and a planar version.

This paper presents some design characteristics of the proposed drives. In addition, this paper presents the integration of the developed drives into a linear positioning stage giving a proof of concept of the proposed drive principle.

2 Development of drive modules

2.1 Working principle

Fig. 1 shows the working principle for the stepping operation mode. Two piezoactuators (A & B) are clamped between a fixed reference and the stator ring. First, piezoactuator B extracts and deforms the stator ring, thereby prestressing it against the slider (a). When piezoactuator A extends and piezoactuator B contracts at the same rate, the stator ring and the slider move horizontally over a distance $\Delta \ell$ (b). Contracting piezoactuator A will remove the prestress between stator ring and slider (c). When piezoactuator B extends, a new stepping cycle can start (d). It is clear that phase (c) is only possible if the slider is supported by other piezoelectric drives.

Fig. 2 shows the working principle for the resonant operation mode. The figure on the left shows a finite...
element simulation of the *horizontal eigenmode*. Driving the piezoelectric actuators in anti-phase will excite this eigenmode. The figure on the right shows the *vertical eigenmode*. Driving the piezoelectric actuators in phase will excite this eigenmode. The stator ring is designed such that the eigenfrequencies of the horizontal and vertical eigenmodes coincide. Driving the piezoelectric actuators at this frequency with a 90° phase difference results in an elliptic motion of the contact point enabling the contact point to drive a slider.

### 2.2 Linear drive module

A linear drive module consisting of two stator rings has been designed. Fig. 3 shows a model of the designed linear drive module. The piezoactuators are mounted between the fixed frame and the stator ring. The stator ring is connected to the fixed frame via leaf springs. A compact and rigid frame ensures the clamped boundary condition of the piezoelectric actuators. Finite element simulation allowed us to detect the horizontal and vertical eigenfrequencies. An iterative process of adapting the stator ring dimensions made it possible to let the horizontal and vertical eigenfrequencies coincide. After simulation a prototype was built. Fig. 4 represents the vertical velocity response for varying frequency of the contact point when two opposing piezoelectric actuators are excited in phase (solid line) and the horizontal velocity response of the contact point when two opposing piezoelectric actuators are excited in anti-phase (dashed line). The measurements show that the horizontal and vertical eigenmodes almost coincide. Table 1

---

*Fig. 2* Working principle for the resonant operation mode

*Fig. 3* Model of the designed linear drive module

*Fig. 4* Measured velocity response function
compares the simulated and measured eigenfrequencies of the drive module.

<table>
<thead>
<tr>
<th></th>
<th>horizontal eigenmode</th>
<th>vertical eigenmode</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEM-simulation</td>
<td>35.6kHz</td>
<td>35.8kHz</td>
</tr>
<tr>
<td>Measurement</td>
<td>34.4kHz</td>
<td>34.2kHz</td>
</tr>
</tbody>
</table>

The vertical stiffness of the module is 30N/µm, the vertical stroke at maximum output voltage is 8µm. Measurements showed drive speeds up to 0.2m/s and traction forces up to 5N.

2.3 Planar drive module

The working principle of the planar drive module is similar to the linear drive module, see Fig. 6. The stator is built up of 2 half-ellipses, connected to the fixed frame via leaf springs. The piezoactuators are mounted inside the stator. The horizontal and vertical eigenmodes show a different sensitivity for the length of the tuning blocks. This way, the horizontal and vertical eigenfrequencies can be matched after production. Fig. 5, left shows the measured displacement of the contactpoint. Fig. 5, right shows the maximum speed of the contactpoint plotted against the measured slider speed at no load condition.
3 Proof of concept on a linear positioning stage

The concept of the presented research is the development of a modular positioning stage integrating the driving and bearing functions. A linear positioning stage has been designed to proof the possibilities of the concept. Fig. 7 shows the design of the linear positioning stage. Two linear drive modules are kinematically mounted into a rigid frame. The drive modules constraint the degrees of freedom in $X$, $Z$ and $\theta_y$ directions. The degrees of freedom in $Y$, $\theta_x$ and $\theta_z$ directions are constrained by air bearings. Fig. 8 shows a picture of the assembled linear positioning stage. Fig. 9 shows the measured traction force characteristics of the linear positioning stage.

Fig. 7: Linear positioning stage

Fig. 8: Assembled linear positioning stage

Fig. 9: Measured traction-force characteristic
4 Conclusion

This paper proposes a novel concept of positioning system integrating the drive and bearing function. Two drive modules—a linear and a planar version respectively—were presented here. A stepping and a resonant operation mode guarantee an accurate and fast mode respectively. A linear positioning stage has been designed in order to proof the concept.

5 Acknowledgements

This research is sponsored by IWT, the Institute for the Promotion of Innovation by Science and Technology in Flanders.

References


