Improved dynamics, resolution and repeatability of a linear positioning system through the use of Piezo Actuator Drive (PAD)

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1.1 Abstract:

In the present paper, the improvements led by the switch to PAD technology for a positioning application are presented.
Several prototypes have been designed, produced and tested in Noliac according to specific requirements. The design includes a reduced gear ratio, leading to benefits in terms of backlash and inertia. Furthermore, the use of PAD allows a simplification of the system, with the suppression of a position feedback sensor and the corresponding control loop. Sub-micron resolution and repeatability down to 2,5µm peak-to-peak were demonstrated, orders of magnitude better than required for that application.
The new design demonstrates very good dynamics. The system reaches its target speed within milliseconds, so start/stop times can be minimised. Furthermore, lower inertia and low friction induce a widened controllable speed. This means that the output can be controlled down to virtually zero speed, allowing a continuous adjustment of its position.
As a result, performance and usage of the positioning system can be improved, leading to quality improvements and cost savings.

Keywords: PAD, piezoelectric, motor, positioning, resolution

1.1.1 Introduction

High precision positioning tasks require a challenging combination of speed and precision. They find applications typically in medical, optical or imaging fields. Most current designs are based on electromagnetic motors. However, electromagnetic motors are not easily controllable at low speed. As a result, high precision systems include a high gear ratio, leading to obvious drawbacks in terms of backlash and inertia, hence precision and dynamics. Acceleration is also a critical parameter. For positioning applications, start/stop times can represent a significant portion of the operating time. By reducing start/stop times, the usage of the machine can be optimised, leading to cost savings.

Piezoelectric Actuator Drive (PAD) [1] can be classified as non-resonant piezo motor, transforming the linear motion of high performance piezoelectric multilayer actuators into a powerful and precisely controllable rotation. Several designs of PAD were developed by Siemens AG in 2000-2008. A partner was needed for commercialisation, and Noliac A/S acquired the PAD technology from Siemens AG in 2010. The particular features of the PAD are its high torque, low inertia and form-fit principle, implying a direct relationship between the applied electrical signals and the position of the motor. With these features, PAD can be advantageous for specific positioning applications are obvious, but some development was required to scale dimensions and performance to the specific application [2].

Fig. 1: *Early PAD prototype, Ø13mm*

Development of a specific PAD for positioning application

The motors are included in a simple architecture. The rotation of the motor is converted into a linear motion through a pinion-rack mechanism. The rack is guided in a linear movement with a series of plain bearings.

Several prototypes have been designed and produced in Noliac according to the requirements for the application (fig. 1). The process included the design and manufacture of specific multilayer actuators providing the required mechanical energy, as well as high precision mechanical parts converting the movement into a controlled rotation. The design includes a reduced gear ratio, leading to improvements in terms of dynamics. These improvements lead to easier start/stop and to a wider controllable speed range. Furthermore, the use of PAD can allow a simplification of the system, with the suppression of a position feedback sensor and the corresponding control loop.

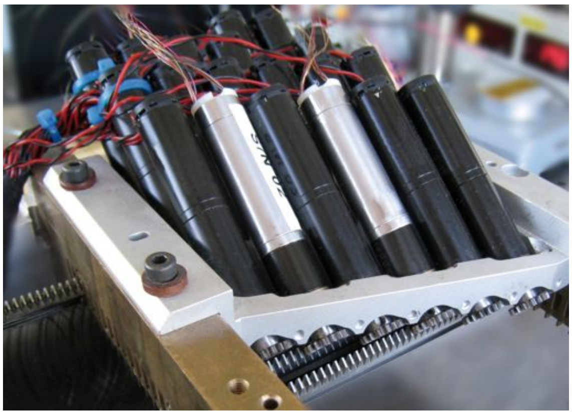

Fig. 2: *Two PAD (metallic cylinders) on a test bench. Note the simple rack-pinion mechanism transforming the rotation into a linear movement.*

The PAD prototypes were mounted on a test bench (fig. 2) and tested in various conditions. The linear position was measured using a high resolution LVDT sensor or a laser triangulation sensor.

Measurement results

Resolution

With the current PAD driver, the theoretical resolution is down to 11 arc-seconds at the motor shaft, corresponding to 66nm at the output. In order to assess performance, the motor was driven to achieve a displacement of about 1mm in one direction (in order to take-up any backlash), then two "steps" of 10 increments corresponding to 660nm. The test was repeated for "steps" of 330 and 132nm. Results can be seen on Fig. 3.

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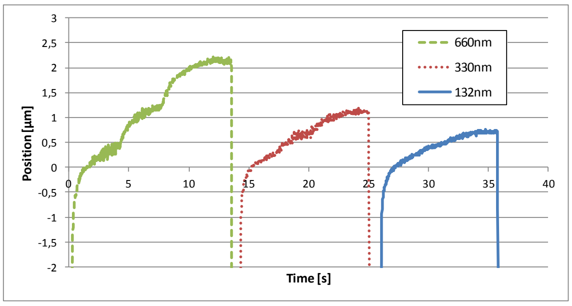

Fig. 3: *Resolution experiment.*
Close-up of the smallest "steps".

Due to noise on the measurement and due to the dynamics of the output such as viscous friction, resolution is difficult to demonstrate below 500nm. This represents however a remarkable result for this application.

Repeatability

In order to assess repeatability, the motor was driven with a specific "staircase" profile, repeated typically 20 times (figure 4). For each of the 4 positions on the profile, repeatability can be assessed (see example on Table 1).

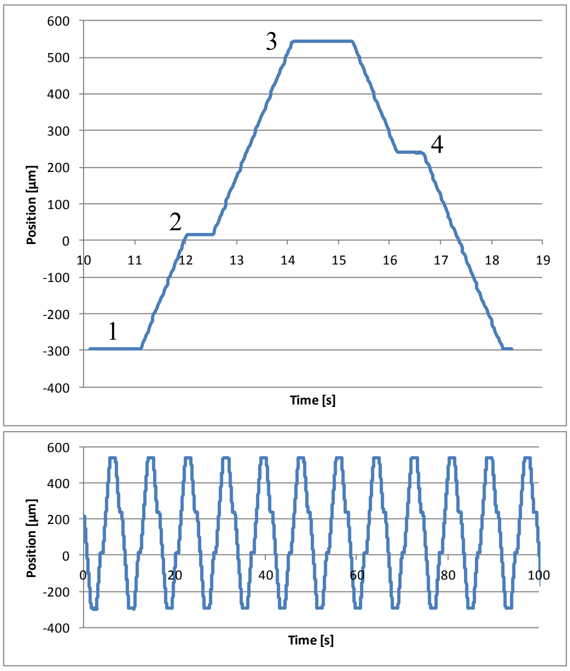

Fig. 4: *Template (top) and repeated profile (bottom) for repeatability assessment.*

The standard deviation on most positions is about 250nm, with a peak-to-peak error under 1µm. Some positions however are less stable, with a peak to peak value up to 2,5µm, probably due to local discontinuities (friction, gearing). This is anyway several orders of magnitude better than required for the application.

Position number [-]	1	2	3	4
Average position [µm]	-296,2	14,84	543,34	239,35
Standard	0,242	0,258	0,271	0,232

deviation [µm]				
Peak-peak error [µm]	0,808	0,786	0,768	0,726

Table 1: *Repeatability results for the profile shown on Fig. 4*

For this simple rack-pinion system, the results have to be mitigated by the relatively large backlash of 220µm measured on the output and mostly due to the gap in the mechanism.

Dynamic characteristics

Compared to the original electromagnetic (E-M) solution, the PAD solution leads to a reduction in backlash and inertia by a factor of 2 and 200 respectively (see Table 2). Friction in the gearing is also reduced.

	E-M design	PAD design
Inertia, equivalent on the output shaft [kg]	159	0,76
Friction [N]	17(1)	2,0(2)
Typical backlash [µm]	400	200

Table 2: *Compared mechanical parameters*
(1) Motor in open circuit
(2) Without PAD. This PAD is normally blocked, so it is not possible to measure friction with the PAD in place.

These parameters are advantageous when it comes to assessing the response of the system to standard profiles.
The most relevant test for this application is the ramp response. This case occurs when the system is in a given position ("productive" time), then required to reach another position while minimising the travel time which is not productive. Systems based on DC motors maximise acceleration by maximising voltage. This results in a trapezoidal acceleration.

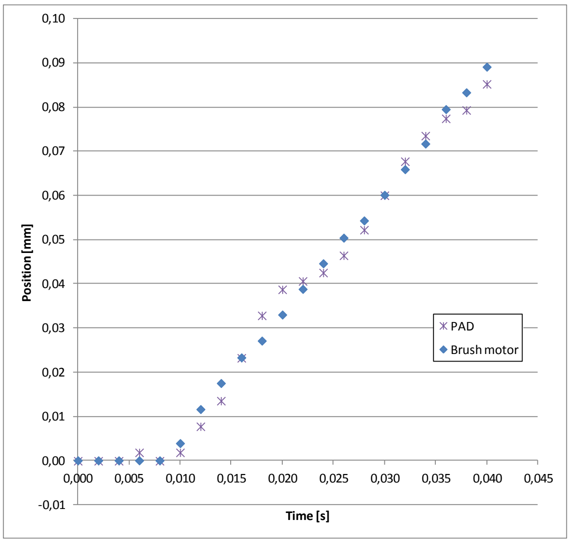

Fig. 5: *Compared start-up profiles for a ramp response of 2,9 mm/s*

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On recordings at 500Hz using a laser displacement sensor (fig. 5), it is not possible to see the acceleration phase. At this level of magnification, both the PAD and the brush motor achieve the acceleration from 0 to 2,9mm/s in under 4ms. This represents an acceleration of 725mm/s^2.
On this recording, the PAD generates some oscillation, due to the dynamic characteristics of the system and the "shock" at start-up. The oscillation is damped within some milliseconds. We believe that this can be improved by using a smoother profile for the acceleration of the PAD.

With the brush motor solution, the "stop" phase is more problematic. If the motor is just disconnected to stop the motion, due to the large inertia it will decelerate with 110mm/s^2, at least 7 times slower than its acceleration. That can create overshoot and make the system difficult to control in terms of its final position.
To reduce "stop" times, it is necessary to decelerate the system by applying a reverse voltage. The voltage pulse in the ms range is however difficult to control as well.

Another interesting feature of the PAD solution is the controllable speed for the system. Electromagnetic motors provide their maximum torque at no speed. For DC motors, speed is commonly modulated by adjusting the voltage applied to the motor. A major drawback is however that in order to maintain a low speed, it is necessary to regulate torque (therefore voltage) so that driving force is minimised. This is made even more difficult by the presence and variability of friction.
PAD systems are directly position-controlled, suppressing the need for any speed control loop. As a result, they can achieve low speeds in a fully controllable way.

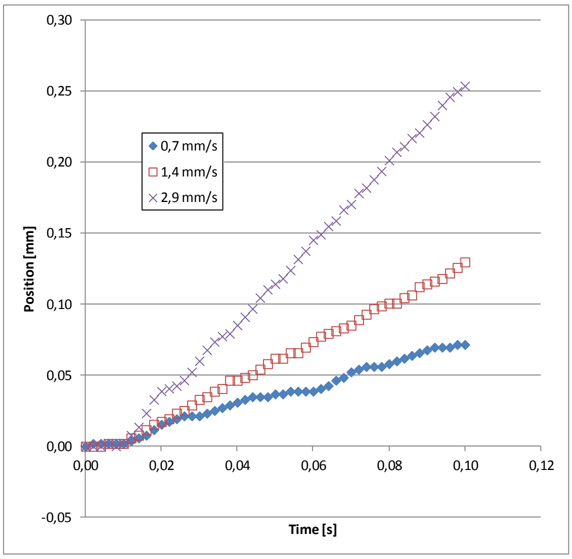

Fig. 6: *Ramp response for speeds of 2,9; 1,4 and 0,7mm/s.*

On the measured profiles (fig. 6) we can see that PAD can be controlled at low speed. The oscillation of the signal is due to dynamic effects following the high start-up acceleration.
With the current driver, the PAD driving frequency can be adjusted down to 2mHz, corresponding to a theoretical speed of 0,14µm/s at the output. This is achieved in open loop and regardless of friction on the output.

Conclusions

With a sub-micron resolution, repeatability in the micron range, ability to run at low speed and simple start/stop behaviour, the PAD technology demonstrated its advantages for specific positioning applications and can therefore lead to a significant performance improvement for future products. Development is still ongoing in order to reach an optimal and production mature solution as well as for developing specific solutions (size, performance).

References

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[1] PAD – Piezoelectric Actuator Drive, Kappel et al., Actuator 2006
[2] PAD - A Scalable Drive Technology, Kappel et al., Actuator 2008

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