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Servo piezo tool SPT400MML for the fast and precise machining of free forms

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Abstract Recent requirements for accuracy and resolution demand higher quality in the machining of precision parts in many industries—such as optics, automotive and aerospace—by free form machining. The required operations are possible by using expensive manufacturing equipment in parallel with several processes such as grinding and polishing. By using a new fast tool servo, the so-called servo piezo tool SPT400MML, driven by a piezoelectric actuator for the precision diamond turning of non-symmetrical surfaces, components can be machined with a fast motion control of the tool (diamond or carbide). The SPT400MML embeds a patented amplified piezoelectric actuator APA400MML and a real-time controller based on a FPGA component able to improve the overall accuracy. Models based on mechanical FEM software and control design software are used to optimise the achieved performances. Experiments have been undertaken to show the capability to displace a diamond tool on a 400-μm stroke with a first resonant frequency of above 600 Hz.

Keywords Piezo actuator · Machine tool · Mechatronic · Real-time closed loop · Aspherical machining · Contact lens machining · Oval piston machining

1 Introduction

This paper presents the development of a fast tool servo application, using a standard product, the amplified piezoelectric actuator (APA; http://www.cedrat-groupe.com/en/mechatronic-products/actuators/apa.html), based on multi-layer ceramics. Mounted in a dedicated mechanical configuration, this novel servo piezo tool (hereafter referred as SPT) is able to machine free form parts quickly and precisely. An SPT is used in a variety of applications where unsymmetrical surfaces are to be machined, such as in the complex trajectory motion machining of pistons or in producing the complicated free form surfaces required in the optics industry. A tool fixed in a light tool holder vibrates in a large bandwidth with the help of an APA piezoelectric actuator. Many aspects such as the performance, size, cost, heat generation, necessary control scheme and potential acceleration are evaluated.

There are two main reasons to implement a SPT on a diamond turning machine [1]. The first is to cancel out repetitive errors that are introduced into a part during the machining process (potential sources of error are external disturbances, resonances in the turning machine structure, spindle/part imbalance, and bearing noise), while the second is to use a SPT on diamond turning machines to machine complex geometries into a work piece. From these applications, SPT can be grouped for these purposes into three categories:

(a) Short stroke (displacements less than 100 μm)
(b) Intermediate stroke (displacements between 100 μm and 1 mm)
(c) Long stoke (displacement greater than 1 mm) [2]

In the past, intermediate stroke could be achieved only with magnetic solutions. With the (patented) APA, piezoelectric materials mix the capabilities of their high stiffness, high achievable bandwidth, high acceleration and long stroke. A mechanical amplifier integrating these multi-layer piezoelectric materials is very promising for the possibility of creating an SPT with a much higher bandwidth than

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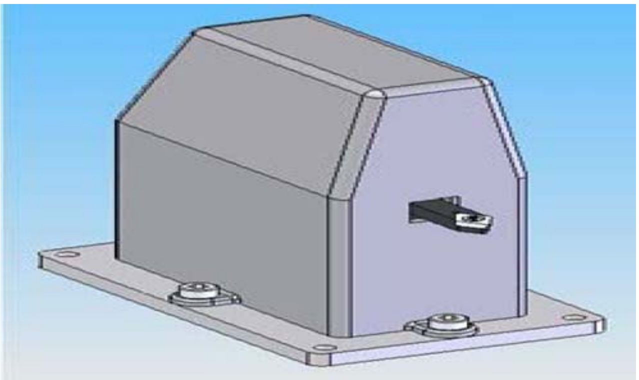


Fig. 1 Overview of the SPT400MML

achievable hitherto. Mechanical and control modeling enables the design of a relevant linear movement.

Experiments, including tests on a specific lathe, show that the diamond tool can be moved up to 500 Hz without re-injected vibration in the machine structure and with a stroke of up to 400 µm.

2 The SPT400MML concept and design

The SPT400MML includes several mechanical and electrical functions (Fig. 1):

(a) The linear motion of the tool holder with fine accuracy;
(b) A dynamic counter-balance of the reactive mass to reduce the impact of the reaction force on the machine;
(c) The sensor to feed the displacement back into the control loop;
(d) Elastic guidance to increase the stiffness in the transverse directions;
(e) A cover to stiffen the SPT and protect it from dust;
(f) To work in a single-point diamond turning operation, the diamond tool must be adjusted in height with a Z stage: an additive stage is used to realise this fine positioning; and
(g) A controller to manage the entire control loop.

Each sub-function has been optimised to improve the performances of the SPT400MML.

Structural dynamic optimisation of the mechanical part was performed:

(a) A front mass reduction allows a higher bandwidth and a reduction in the weight of the device.
(b) A modal analysis aims at optimising the structural dynamic behaviour.

The SPT400MML is based on the standard APA400MML. The theoretical frequency resonance (in block-free configuration) for such an actuator without linear elastic guidance is 634 Hz

$$f_R = \frac{1}{2\pi}\sqrt{\frac{K_1}{M}} \tag{1}$$

with M=−33 g. Using linear elastic guidance, the stiffness is changed from 0.52 to 0.59 N/µm and the resonance frequency increases to 675 Hz

$$f_R = \frac{1}{2\pi}\sqrt{\frac{K_2}{M}} \tag{2}$$

Finally, the additional mass placed on the actuator frame (i.e. tool holder and tool) is 5.5 g.

As a conclusion, the theoretical resonance frequency (block-free) of the SPT-loaded actuators becomes

$$f_R = \frac{1}{2\pi}\sqrt{\frac{K_2}{M+m}} = 624\text{ Hz} \tag{3}$$

A first modelling action is to analyse the mechanical behaviour of the SPT to obtain a dynamic equilibrium between the tool holder and a back mass. Second, the tool holder is optimised with a light mass, to be compatible with standard diamond tools from Contour Fine Tooling (http://www.contour-diamonds.com).

The first mode matches the transversal vibrations that occur in the SPT at 398 Hz; the second mode is the asymmetrical mode of the pair of APA that occurs in the actuation direction at 521 Hz; whilst the third mode is the symmetrical mode of the pair of APA in the actuation direction, which occurs at 657 Hz. The theoretical resonance frequency is quite close to the third mode (624 vs. 657 Hz).

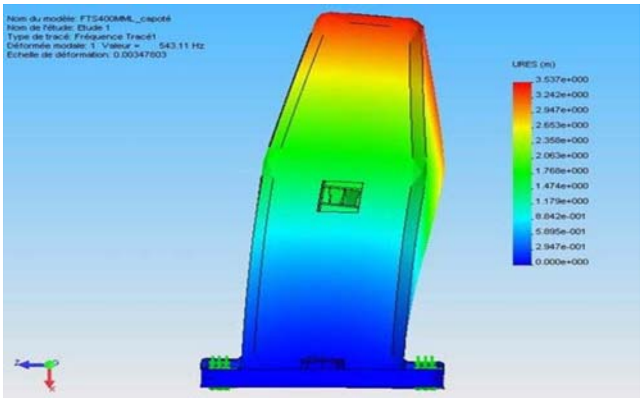


Fig. 2 SPT400MML modal analysis with cover stiffener

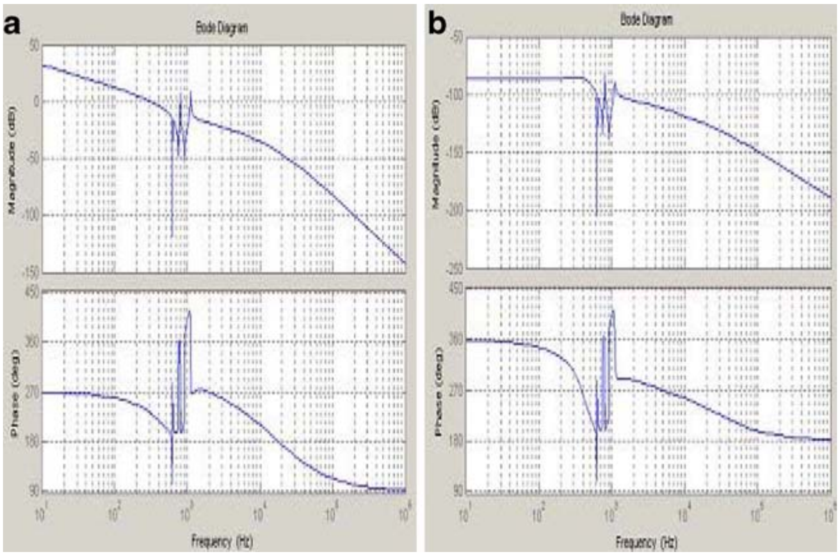


Fig. 3 Modelling results in open and closed loop: **a** open-loop modelling; **b** closed-loop modelling

To obtain a safe design from the off-the-shell piezoelectric actuator, several optimisations were performed, as indicated below:

(a) Increasing of the stiffness of both actuators to postpone the flexural mode without changing their stiffness in the actuation direction.
(b) An additional transversal stiffness is required to remove the transverse vibrations, the cover becoming necessary to fulfil this requirement (see Fig. 2).
(c) The stiffness in the actuation direction needs to be increased to postpone the asymmetrical mode.

The results are then even better in terms of postponing parasitic modes. In addition, the mass and stiffness are balanced.

3 Control of the SPT400MML

Following the dynamic mechanical analysis, an electromechanical model is built to analyse the behaviour of the control loop by including the driver-and-sensor behaviour and discrete functions as the sample and hold components. This modelling phase enables the optimisation of the regulator to achieve the best performances under closed loop when following a sine command.

The feedback control loop, based on a robust proportional integral derivate (PID) regulator plus a specific stabilising filter, is used to control the mechanical system. A stabilising filter is placed behind the PID regulator to reduce phase shift and gain at high frequency.

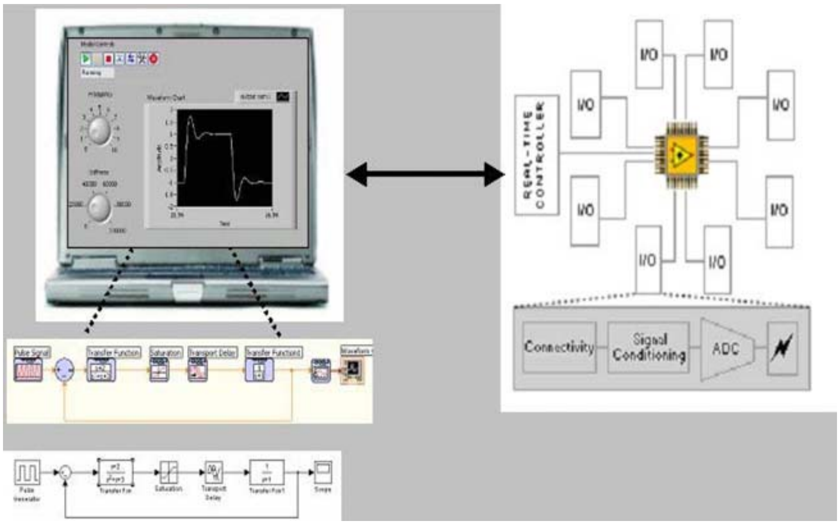
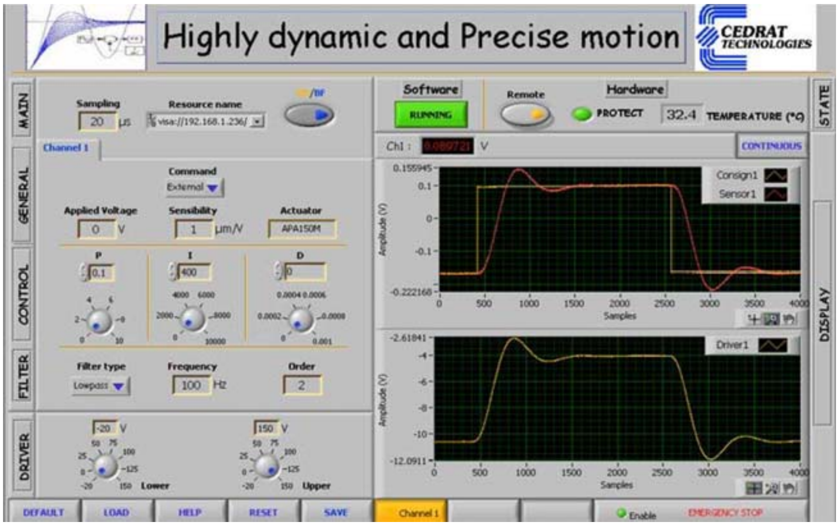


Fig. 4 Combination of a FPGA real-time target and a graphic structure to control the SPT400MML



Sampling 20 µs
Resource name visa://192.168.1.236/
Command External
Applied Voltage 0 V
Sensibility 1 µm/V
Actuator APA150M
P 0.1
I 400
D 0
Filter type Lowpass
Frequency 100 Hz
Order 2
-20 V Lower
150 V Upper
Software RUNNING
Hardware PROTECT
32.4 TEMPERATURE (°C)

Fig. 5 Human machine interface of the controller

In piezoelectric applications, it is advisable to use a sampling frequency of at least 30 times the cross-over frequency of the continuous design to preserve the behaviour of the continuous system to a reasonable degree. The sampling rate of the entire loop is chosen to be close to 20 µs. The quantization of the analogue signal is 2^{-16} to be compatible with the high resolution of the SPT400MML.

The modal analysis is done in open and closed loop to analyse the impact of the higher parasitic modes. Indeed, these modes can destabilise the loop. To reduce such impact, a solution is to place stop-band filters on specific resonant modes to reduce their impact in closed loop.

The modelling results show the possibility of obtaining a high bandwidth of up to 500 Hz. The dynamic stiffness at 10 Hz is increased by 100 to reduce the impact of the residual vibrations of the machine (Fig. 3).

The limits are the destabilising higher modes and the current capability of the driver. It must be borne in mind

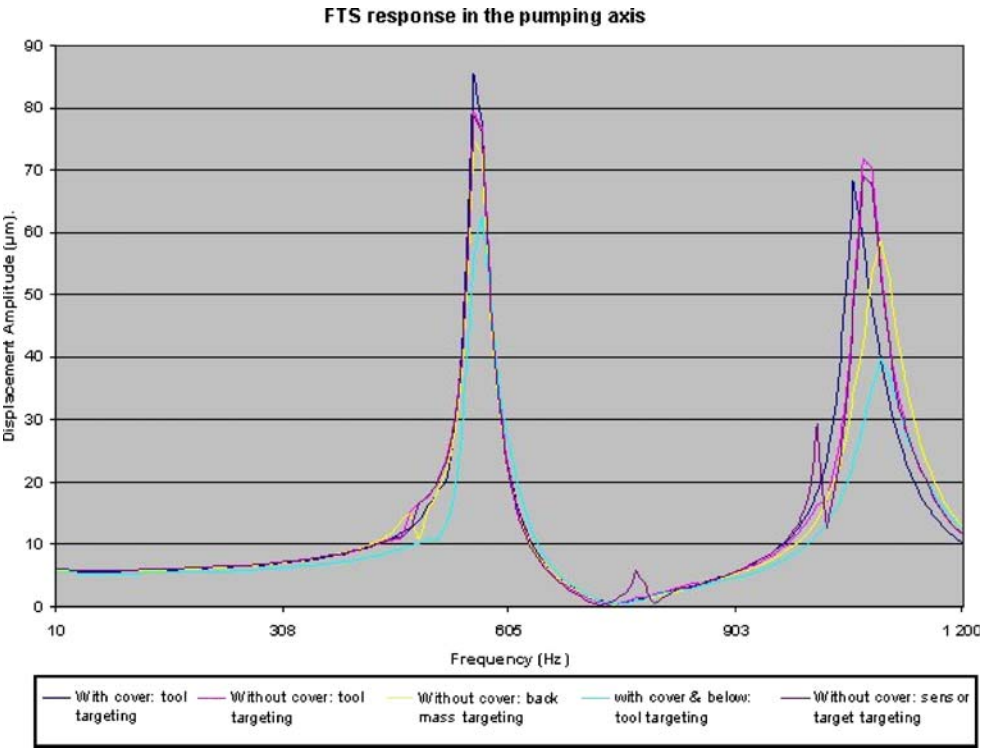


Fig. 6 Admittance measurement of the SPT400MML

that the piezoelectric actuator has a high-quality factor that may not be compatible with a standard regulator.

From the electrical point-of-view, the mechanism is driven with a dedicated rack, including:

(a) A more powerful driver to improve the couple bandwidth stroke. With the ±2.4 A output current capability, it is possible to drive the 2 APA400MML in parallel (the acting actuator and the counter balance) in full stroke up to 112.5 Hz.
(b) A position sensor based on eddy current technology able to provide fine accuracy (±0.25% of the full scale) and a fine resolution (up to 25 nm rms with a bandwidth of 500 Hz).
(c) A controller built on the new real-time UC75 (see Fig. 4), including a real-time target, able to improve the performance of the control techniques of the actuators. This solution is chosen with regard for the high sampling rates needed to control the first modes of the SPT400MML.

The UC75 includes a National Instrument Core based on Compact RIO@NI and the power of the Labview@NI Libraries to control any system with fast ticks with a deterministic time of up to 100 k sample/s simultaneously on four channels.

The CompactRIO is powered by reconfigurable I/O (RIO) FPGA technology (Fig. 4).

The net sum is the speed, parallelism and power of FPGAs and presents a powerful platform for implementing a control loop with a fast parallel process as a tracking servo, all running with absolute timing determinacy to drive

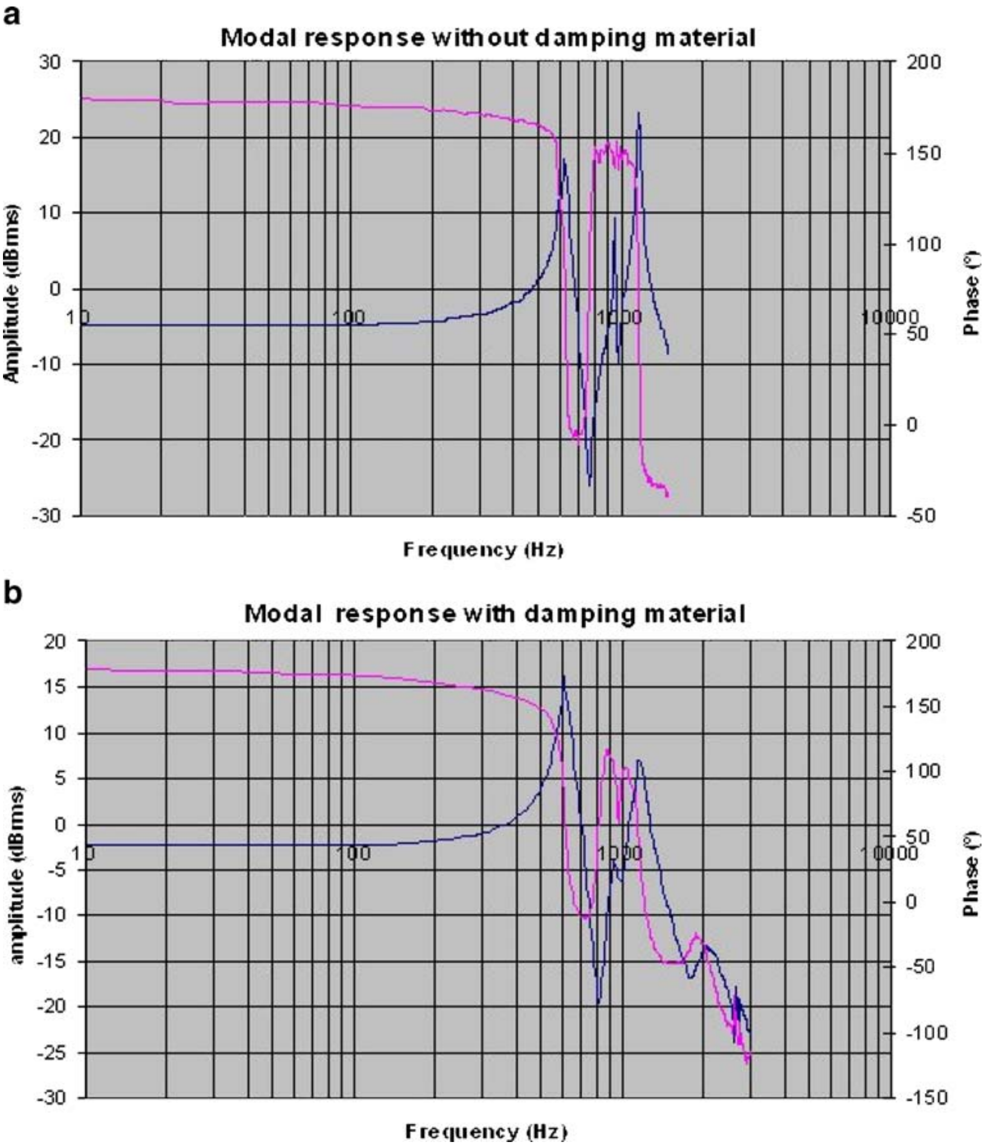


Fig. 7 Modal response: **a** without and **b** with a damping material

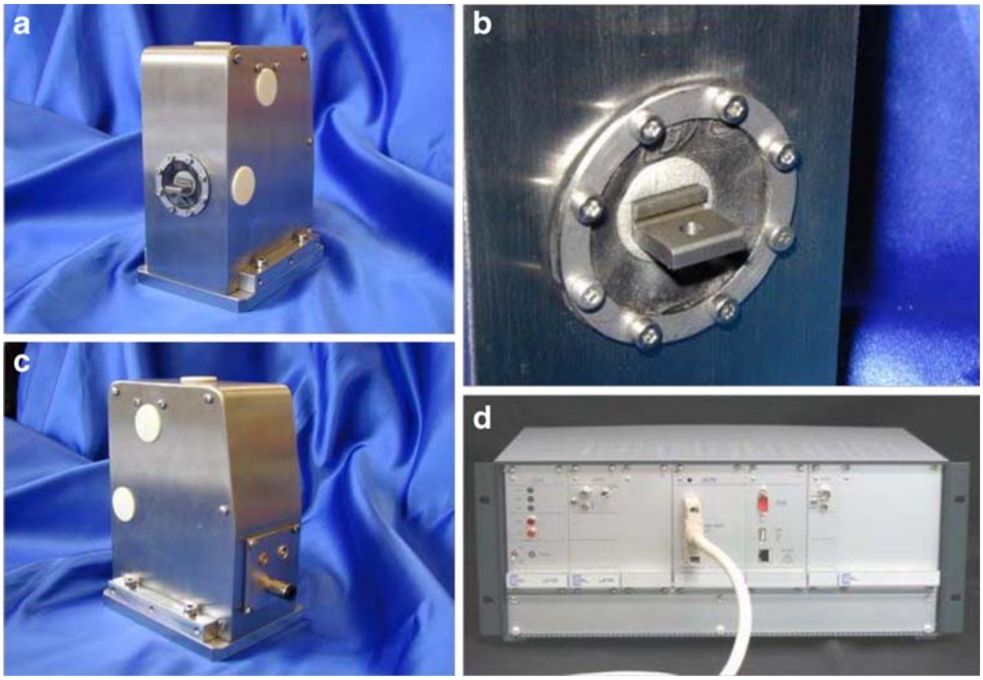


Fig. 8 Final assembly of the SPT400MML mechanical part and its dedicated controller: **a** front face mechanical part of the SPT400MML; **b** zoom on the mechanical interface with the light tool holder; **c** back face with electrical and air interfaces; **d** dedicated electronic cabinet

and control the actuators of Cedrat Technologies. The following human machine interface is used to control and monitor each parameter of the loop (Fig. 5).

4 Experimental results

After the manufacturing and assembly phases, some functional tests were performed to analyse the behaviour of the system in open (Fig. 6) and closed loop (Fig. 7).

The experiment is composed of an open-loop analysis to obtain the modal landscape of the mechanism (see Fig. 7) and a retro-fit to tune the different parameters of the controller to optimise the closed response in terms of both bandwidth and accuracy.

Figure 7a, b is very interesting because a magnified frequency can be seen at around 1,100 Hz: this is a mode from the added mass at the tip of the SPT400MML coupled with the guiding blades. These parasitic modes can destabilise the closed loop and so must be minimised. The mechanism is damped with silicon material to reduce the quality factor of each mode (patented): the amplitude of the mode at 1,100 Hz is reduced by 3 (Fig. 8).

The maximum bandwidth (i.e. when the bandwidth is optimised) is close to 500 Hz with an error of ±0.5 dB. This performance can be minimised with a lower bandwidth (the regulator parameters are tuned to reduce the error; Fig. 9a, b). A performances synthesis is presented in Table 1.

5 Conclusions

A new fast tool servo has been developed and manufactured: it includes a mechanical part (SPT400MML device) and its dedicated controller/driver. After the mechanical and control design phases, some trials on the SPT400MML were performed. The first results showed a mechanical part composed of multi-mode frequencies. These higher modes gave some results in closed loop but limited the performance due to instability.

An optimisation based on the introduction of damping materials between the blades of the actuators gave better results.

The best performances were established with stop-band filters placed at different frequencies, the final bandwidth achieved being close to 500 Hz with an error of 10% at 500 Hz. At 100 Hz, the error is close to 2%, this error being due to the controller alone.

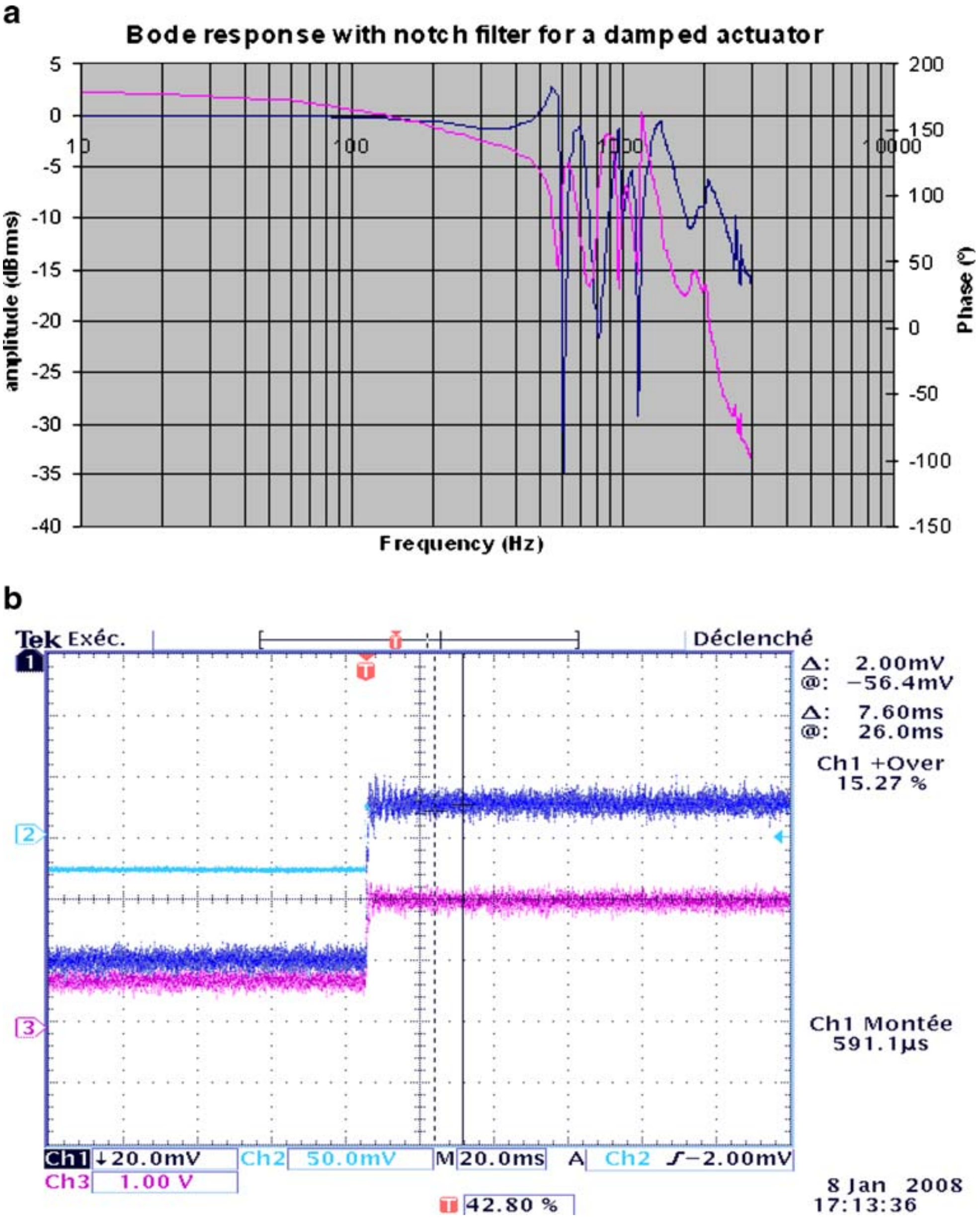


Fig. 9 Responses of the SPT400MML in closed loop (**a** bode and **b** transient)

Table 1 Performance synthesis

References	Unit	SPT400MML
Notes		Preliminary
Technology baseline	None	APA400MML
Stroke (a)	µm	400
Force capability	N	10
Bandwidth (b)	Hz	up to 450
Typical spindle speed	rpm	6,000 or 100 Hz
Position noise floor (c)	nm rms	15
Linearity (d)	%	2
Resonant frequency	None	Above 600 Hz
Sensor	None	Eddy current sensor
Excitation voltage	Volts	–20 to 150
Type of control loop	None	Feedback control
Tool holder	None	Light shank 6.35 mm cross-section
Dimensions	mm	140×100×75
Mechanical interfaces	None	4M3 holes
Other	None	Back mass dynamic compensation

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