23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

A NEW ASSISTED TOOL HOLDER FOR ULTRAPRECISION MACHINING: EXPERIMENTAL TESTS

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Abstract. *This paper presents the bench and machining tests of an assisted tool-holder (ATh) used for precision and ultraprecision machining. The ATh works as a fast tool servo by using a piezoelectric actuator to the displacement of the diamond tool, a capacitive sensor to get displacement feedback and a PID controller for positioning correction, the control program was developed in the software LabView®. Such control corrects the effects of hysteresis due to piezoelectric crystals, and therefore its possible positioning errors. The bench tests were performed in empty (without material to be machined) with four different wave signals: sine, square, triangular and sawtooth. The machining tests were held in sine and square wave signal. By comparing the input signals (user-supplied) and output (run by ATh) obtained in the displacement bench tests, it was analyzed the integrity of displacement generated in function of time. Ultraprecision machining of sine waves and square waves in aluminum AISI 6000 showed great precision in the mechanical design and ATh control system.*

Keywords: *Assited tool holder, Ultraprecision Machining, Control.*

1. INTRODUCTION

Components with reduced size and weight are a project requirement in several technological areas. While in some cases this demand is an optimization strategy or a customer exigency, in other cases it can be essential for the project functionality.

An increasing attention is being given at the microcomponents fabrication techniques. In this context, there is the ultraprecision machining which can be used for the production of molds used in the manufacture of microcomponents, what allows the production of parts with precision of sub-micron shape and roughness of nanometer order (Ikawa, *et al*., 1991).

The ultraprecision machining gained relevance in the manufacture and world economy. LED screens, AMOLED, mechanical components and military equipment are some of the applications that use this technology.

The Assisted toolholder (ATh) that uses piezoelectric actuator allows more precise shifts, and together with the computerized numeric control and compensation systems of geometric and thermal errors, it aims to enable the high precision machining.

Kouno (1984) designed a ATh consisting of two parallel bars, with stiffness 300 Nμm-1 with 6 microns of displacement and 50 Hz of maximum frequency. It used a LVDT sensor and a closed mesh controller.

Dow *et al*. (1991) designed and built a ATh for machining with optical finish. He used laser interferometric and concluded in his work that he could not measure very high frequencies. He machined topographies of 2,5μm of depth with clam rotation of 500 rpm and 10 Hz of a waveform generated.

O'Neal *et al*. (2001) developed a system with ATh and workpiece positioning regulators for machining in a drill, getting 40% increase in length of drills with error within 95.4% confidence interval.

Kim *et al*. (2004) designed a ATh getting to manufacture aspheric mirrors of 620 mm of diameter with an accuracy of 0.7 mm deep.

Kim *et al*. (2009) and Gan *et al*. (2007) did a study of rigidity in all three directions (x, y, z) of the tool holder, obtaining 4.6 microns and 69 Hz.

Tian *et al*. (2009) found that the contact condition between the actuator and the rigid part of the tool holder was affected when it had a low stiffness, and with the fatigue analysis, using FEM (finite element tool), he could a stiffness value of 13.1 Nμm-1. For smaller displacements, it was obtained high-frequency dynamics, of 1100 Hz order.

Huo and Cheng (2008), on the other hand, stated that with higher stiffness, using actuator frequency equal to the first natural frequency of the tool holder there is a reduction of the piezoelectric actuator effectiveness. Therefore, the theoretical calculation and FEM analysis of the tool holder were used to define the scale and first natural frequency.

A study of the piezoelectric actuator self-positioning control was made by Badel *et al*. (2008), which uses a sensing model in place of a positioning sensor. The comparison between the systems proved satisfactory. The same author proposed an active vibration control and hysteresis compensator (Badel, *et al*., 2014).

In this context, this article presents the high precision machining results performed with a ATh and positioning control system. The design of this tool holder combined the dynamic behavior analysis of the ATh and its static analysis, according to the characteristics of each component to be used (an actuator and displacement sensor).

2. ASSISTED TOOL HOLDER (ATH) AND POSITIONING CONTROL SYSTEM

The ATh used is the assisted tool holder for precision and high precision machining from Javarez and Duduch (2012), which can be seen in Fig. 1. This device contains 6 major components: 1. ATh base, 2. Damping springs, 3. Tool holder, 4. Capacitive sensor base, 5. Capacitive sensor and 6. Piezoelectric actuator.

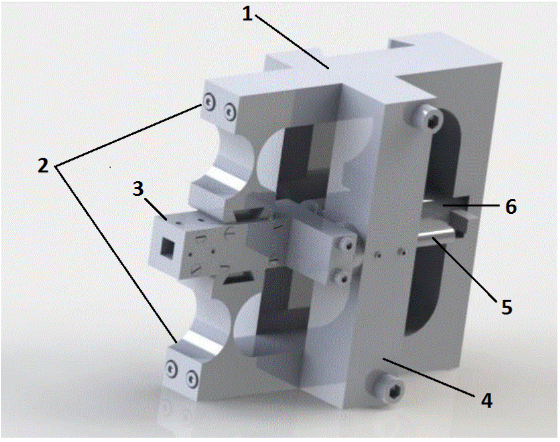

Figure 1. Rendered ATh model.

The project follows the principles of high precision machine designs, including the alignment and symmetry and it does not contains moving parts, and the piezoelectric actuator and the tool holder are firmly seated to eliminate noise and imperfect contacts.

This ATh is designed to meet the following requirements:

- Quick change tool
- Alignment symmetry
- Elastic recovery to assist in the return of the positioning
- Natural Frequency medians
- Range (30 microns), actuator capacity
- Fatigue, with increase in component lifespan

It was used a proportional-integral-derivative control system (PID) to control the position. This system makes the interaction between the positioning measured by the sensor and it corrects the position of the piezoelectric actuator (Figure 2). The data processing for control is accomplished through the Labview® 2010 software.

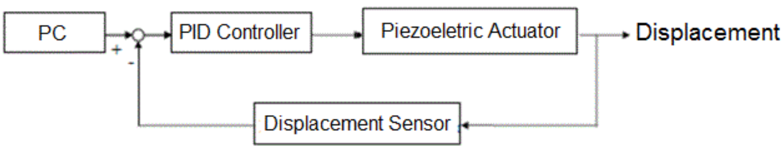

Figure 2. Control Diagram.

The inverted double C springs aim to cushion the displacement provided by the piezoelectric actuator, slowing down at the end of the shift. This kind of spring has the advantage of not having right angles which are concentrators of stress and can lead to premature failure.

Hereafter, it is presented the results of bench tests and experimental of machining. The tests are conducted with a spring of 0.5 mm of neck thickness, this value was chosen based on FEM simulations (finite element method) and parameterization values as tool offset, actuator force and spring reaction force and material to be used, obtained in

ANSYS® (Javarez, *et al.*, 2013). For experimental tests sample analysis is used contactless optical instrument VEECO® Wyco NT1100, which enables the measurement and comparison with the results of the bench test.

2.1 Bench test

In the bench test the tool operates in vacuum and the machining does not occur. It is assumed as valid the bench tests, due to the fact the strength of machining is very small, because it is micrometric displacement. This test is essential to prepare the system for the experimental test machining.

The first step is to check the hysteresis of the ATh set provided by the piezoelectric actuator. This time, the PID control is not active. Only the position resulting from the tension applied to the piezoelectric actuator is measured. It is varied the voltage tension from 0 to 800V, noting the result of displacement of 100 in 100V.

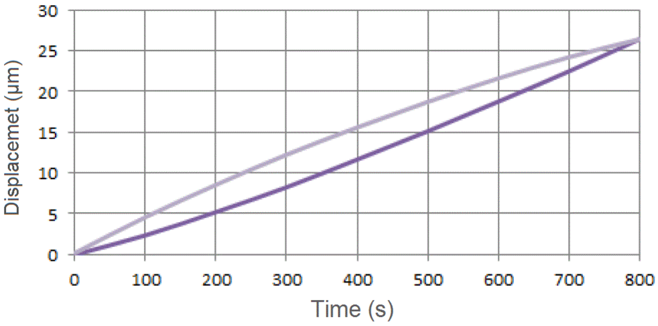

Figure 3. Hysteresis of the ATh.

It is shown in Fig. 3 the ineffectual of displacement before and after the withdrawal of the voltage in the actuator. Here, it can be clearly seen the nonlinearity of the graphic, a fact evidenced by the hysteresis due to the piezoelectric crystals, already known (Badel, *et al.*, 2014). Thus, the control of this positioning error must be instantaneous and performed by the capacitive sensor reading and properly by PID control.

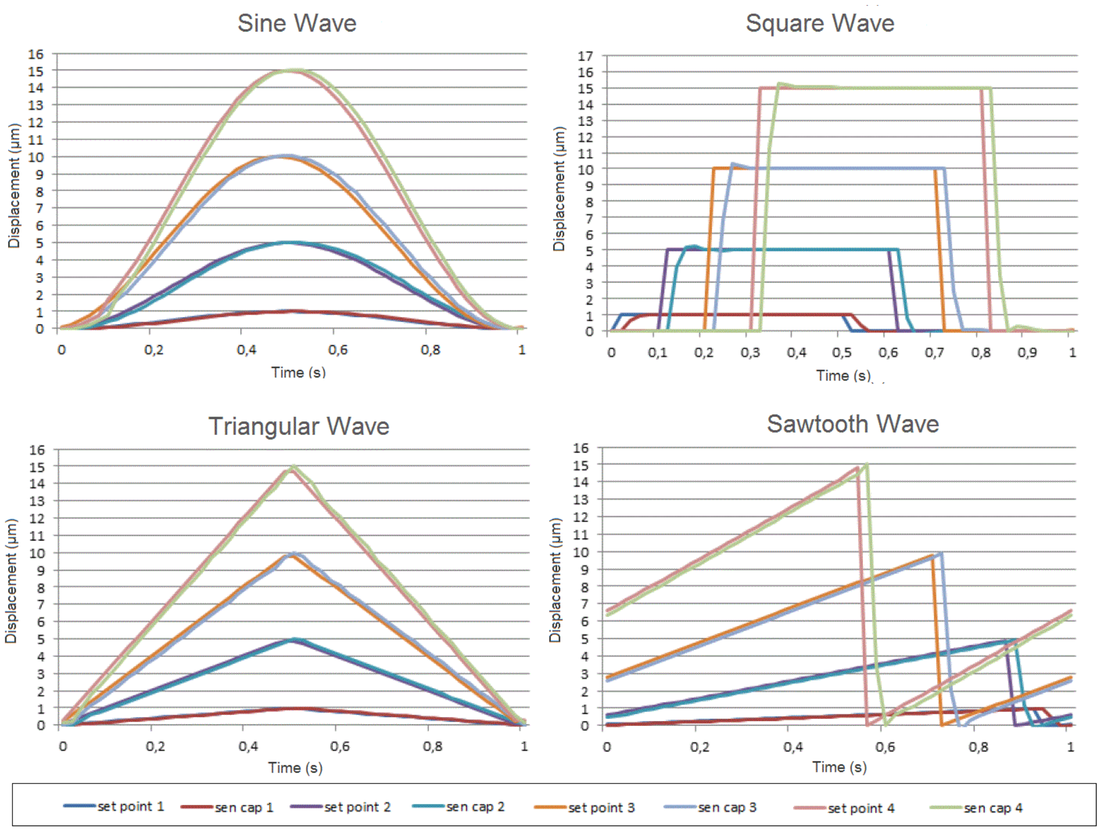

Figure 4. Displacement as a function of time in different waveforms.

Applying, then, the PID control it was obtained linearity of the acquired signals (set point) and the measured displacement (capacitive sensor) through preselected waves in the positioning control.

To analyze the effectiveness of this movement and its control, this paper analyzes this position as a function of frequency for sine, square, triangular and sawtooth waves, and also compares the results of the acquired signal and the displaced.

Figure 4 shows the acquired results. To get such data, it was varied the amplitude set point of 1, 5, 10 and 15 micron for a displacement lasting 1 second and 1 Hz of frequency. In the figures caption, sin cap is an abbreviation of capacitive sensor displacement reading, and the set point is the displacement value required by the user. The set point 1 and the sin cap 1 refer to 1 microns displacement of the tool holder and hence of the machining tool. Set point 2 and sin cap 2 refer to 5 microns, set point 3 and sin cap 3 refer to 10 microns, set point 4 and sin cap 4 refer to 15 microns, all from the same ATh tool holder.

All graphs demonstrate that the displacements have constant behavior of period and amplitude over time. It can be noted the presence of overshoot immediately after each wave reaches the maximum displacement and small delay wave displacement sensor in relation with the set point of the square and sawtooth waves. This behavior is more characteristic in square waves and degree functions due to the inertia of the displacement of the mechanical assembly very quickly in a very short time, what is minimized when the PID controller is properly adjusted.

2.2 Experimental test machining

The machining test analyzes the ATh behavior in relation to the parameters demonstrated in bench test. The machining reaction force can be considered irrelevant considering the material to be machined (aluminum AISI 6000) and the small depth of machining. The lathe used is the Rank Pneumo ASG 2500.

The machining tool to be used in this experiment is diamond tip one face cutting CONTOUR CO30LG model. A schematic model of the tool is shown in Fig. 5, the tip having a radius of 0.76 mm, front clearance angle of 11° and back rake angle 0°. Although, Figure 5 shows the assembly positioned for machining.

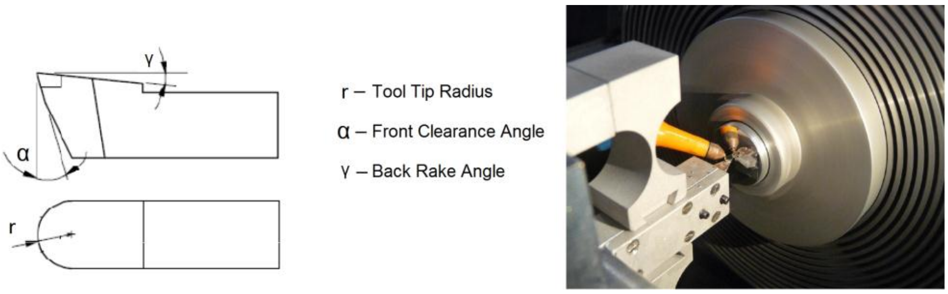

Figure 5. Diamond tool CONTOUR® CO30LG model and positioning system.

After the completion of the mirroring surface sample, the ATh control system, the PID controllers, the waveform, amplitude and frequency were set; and it was carried out the operating procedures of the CNC.

In order to assess the integrity of the machining, it is adopted standard rotation for the experiments of 120 rpm or 2 Hz. To analyze the entire profile of a complete waveform, made in a second, or 1 Hz, it is adopted multiples of rotation of 60 rpm. Thus, with the frequency of 10 Hz in rotation around 120 rpm, it comes to happen the machining of 5 waves of two types of shape, sinusoidal and square.

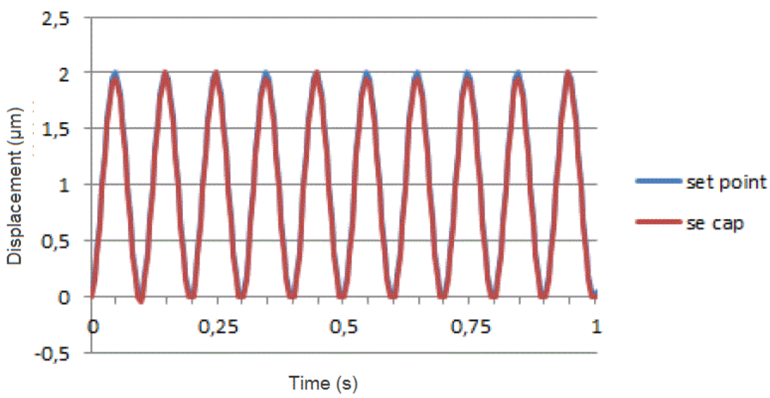

Figure 6. Machining signa of the sine wave, with 1 µm of amplitude.

When machining with sine waves, CNC data is adjusted to feed 0.05mm/turn and rotation of 120 rpm, and the control system is set to a sine wave frequency of 10 Hz and amplitude of 1 microns and total depth of 2 microns.

The result obtained in machining with this configuration is shown in Fig. 6, and it can be observed that the section obtained is equivalent to the results in the corresponding bench test, showing that the interference of the machining force is very small. Figures 7 and 8 present the result obtained in VEECO® 3D scanning microscope. It can be seen in Fig. 7 the maximum displacement of 2 microns corresponding to the acquired signals of shifts in Fig. 6.

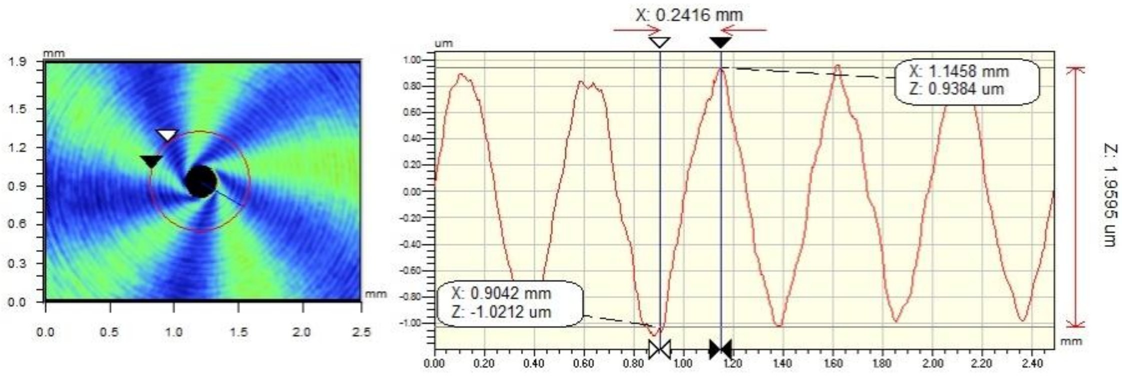

Figure 7. Machining Analisys of sine wave, with 10 Hz frequence 2 μm depth.

The shape of five sine waves is also clearly visible in Fig. 8, similar to the analysis shown in Figures 6 and 7. The feed used was 0.05 mm / revolution.

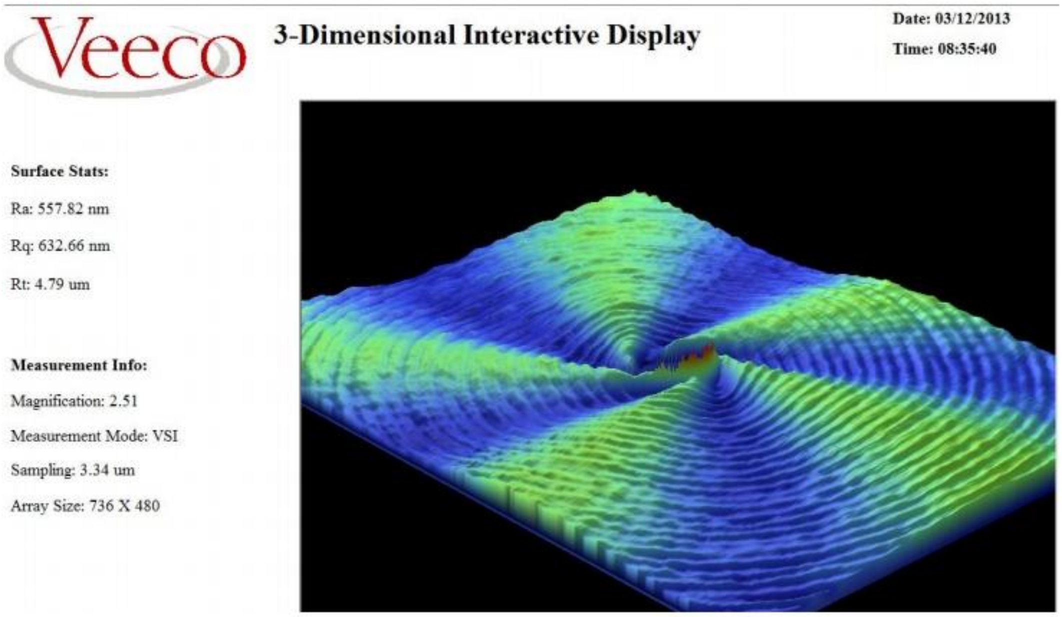

Figure 8. View of the machined surface with sine wave.

The analysis of the linearity of the ATh control system, the generated waves, with their shifts remained constant. The surface finish and surface roughness are not analyzed because they are not part of the scope of this work.

For machining with square waves it is also adjusted CNC data to rotation of 120 rpm, and the control system is set for sine wave frequency of 10 Hz and amplitude of 1 microns and a total depth of 2 micrometers. The adjusted progress in CNC is 0.5 mm / rev.

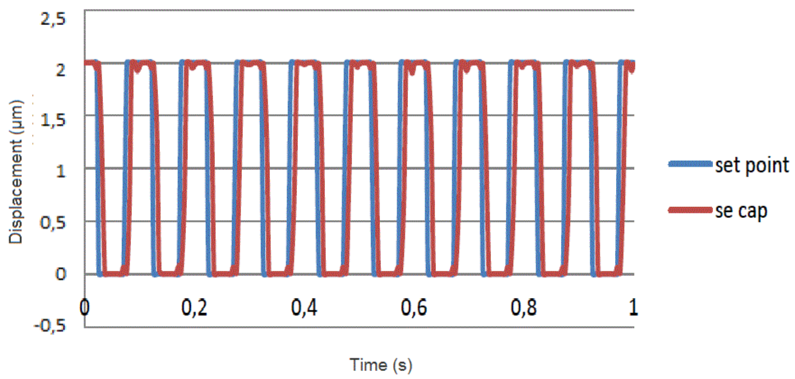

Figure 9. Machining signa of the square wave.

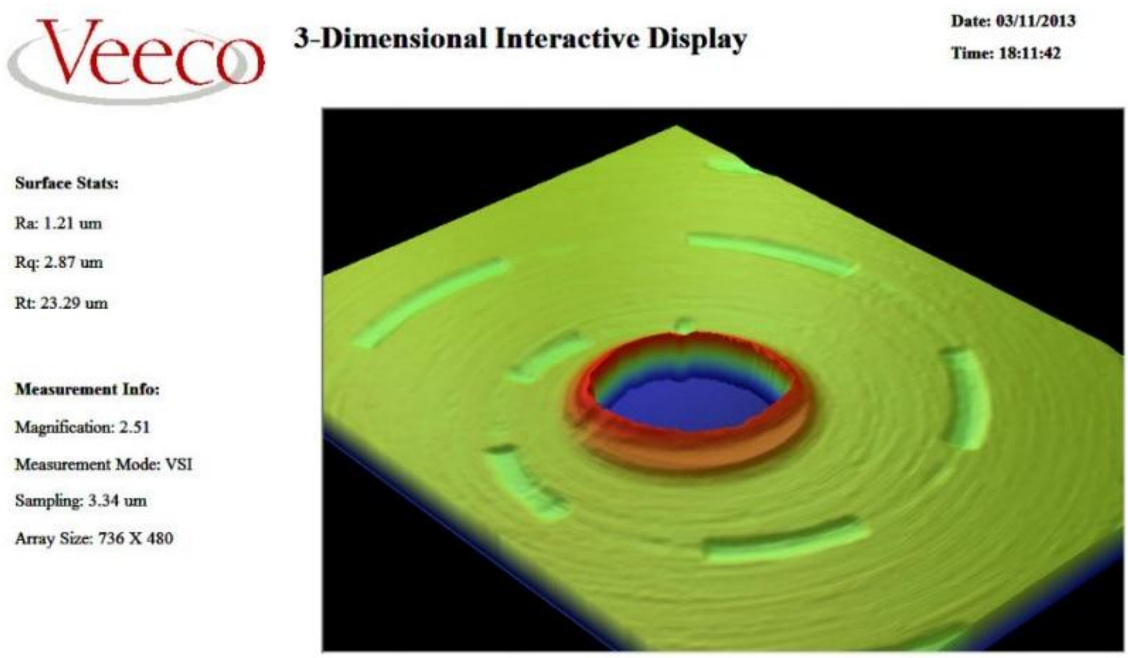

Figure 10. View of the machined surface with square wave, with 0,5 mm/turn.

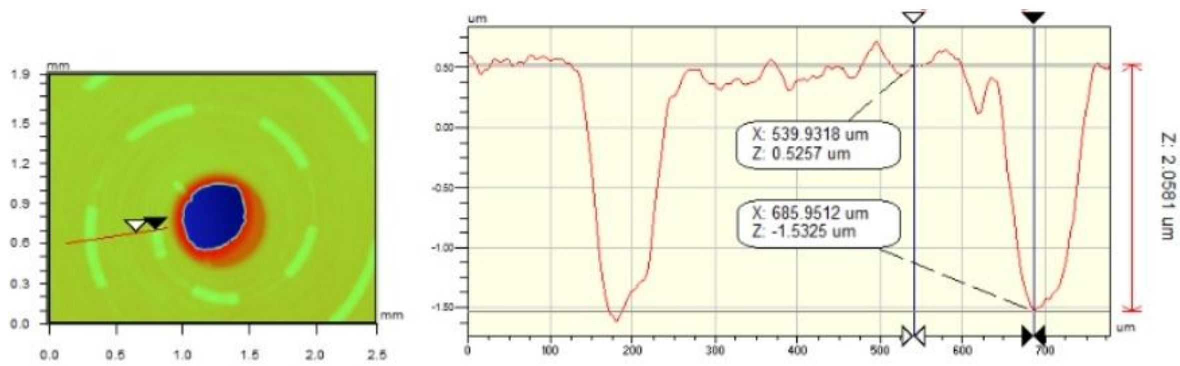

Figure 11. Machining Analisys of sine wave, with 0,5 mm/turn.

To advances of 0.5mm/turn, results are shown in Figures 10 and 11. Data interpretation of machining with square waves is also close to the results obtained in bench tests with 2μm deep and square wave profiles.

3. CONCLUSION

This work contributes towards a long-term project of the EESC-USP Precision Engineering Laboratory allowing the design and validation of a new model for ATh high precision machining.

From our tests, it is possible to verify the integrity of displacement generated as a function of time. There were no major changes in the required displacement (set point) of the cutting tool in amplitude function generated; data of the program Labview® controller registers the linear variation of only 0.1%.

These analyses ensure the functionality of the ATh and validate its mechanical project, as well as its control system. It follows, therefore, that the ATh from Javarez and Duduch (2012) allows perform machining work of surfaces and complex parts, symmetrical or not, enabling a wide range of use of the machine and the types of parts produced by it.

4. AKNOWLEDGMENT

Thanks to the program Fundação Araucária – Paraná/Brasil for the undergraduate research scholarship, and to the Universidade Tecnológica Federal do Paraná (UTFPR) and Universidade de São Paulo (USP) for the support in this research.

5. REFERENCES

Badel, A., Breton, R. L., Formosa, F., Hanene, S. and Lottin, J. 2014. Precise positioning and active vibration isolation using piezoelectric actuator with hysteresis compensation. Journal of Intelligent Material Systems and Structures. v. 25, p. 155-163.

Badel, A., Qiu, J., Sebald, G. and Guyomar, D., 2008. Self-sensing high speed controller for piezoelectric actuator. Journal of Intelligent Material Systems and Structures. v.19 p. 395-405.

Dow, A. T., Miller, H. M. and Falter, J. P., 1991. Application of a fast tool servo for diamond turning of nonrotationally symmetric surfaces. Precision Engineering. v. 13 p. 243-250.

Gan, S. W., Lim, H. S., Rahman, M., Watt, F., 2007. A fine tool servo for global position error compensation for a miniature ultra-precision lathe, Int. J. Mach. Tool. Manu. v. 47 p. 1302-1310.

Huo, D. and Cheng, K. 2008. A dynamics-driven approach to the design of precision machine tools for micro-manufacturing and its implementation perspectives, in: Proceeding of Imech Part B: Journal of Engineering Manufacture. v. 222 p. 1-13.

Ikawa, N., Donaldson, R. R., Komanduri, R., Konig, W., Mckeown, P. A., Moriwaki, T. and Stowers, I. F, 1991. Ultraprecision metal cutting – The past, the present and the future. Annals of the CIRP. v. 40. p. 587-594.

Javarez Jr., L., Duduch, J. G. and Gonçalces, A. M., 2013. Design and construction of a novel assisted tool holder. In: 13th euspen International Conference, Berlim. Proceedings of the 13th euspen International Conference, p. 220-223.

Javarez Jr., L. and Duduch, J. G., 2012. Porta ferramenta assistido para usinagens de precisão e ultraprecisão. BR n. PI 10.2012.031753.2, 13 dez 2012.

Kim, H. S., Kim, E. J. and Song, B. S., 2004. Diamond turning of large off-axis aspheric mirrors using a fast tool servo with on-machine measurement. J. Mater. Process. Tech. v. 146 p. 349-355.

Kim, H. S., Lee, K. I., Lee, K. M. and Bang, Y. B., 2009. Fabrication of free-form surfaces using a long-stroke fast tool servo and corrective figuring with on-machine measurement, Int. J. Mach. Tool. Manu. v. 49 p. 991-997.

Kouno, E., 1984. A fast response piezoelectric actuator for servo correction of systematic errors in precision machining, Annals of the CIRP, v. 33 p. 369-372.

O'Neal, G. P., Min, B. K., Pasek, Z. J. and Koren, Y., 2001. Integrated structural/control of micro-positioner for boring bar tool insert. Journal of Intelligent Material Systems and Structures. v. 12 p. 617-627.

Tian, Y., Shirinzabeh, B. and Zhang, D., 2009. A flexure-based mechanism and control methodology for ultra-precision turning operation, Precision Engineering. v. 33 p. 160-166.