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ULTRAPRECISION LATHE QUALITY IMPROVEMENT THROUGH EFFECT ANALYSIS

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Abstract. *During the 90`s, an ultraprecision lathe was assembled in the Precision Engineering Laboratory (LMP) at Federal University of Santa Catarina (UFSC), based on a design methodology to reconfigurable precision systems. This lathe was first designed to assure dimensional and surface quality for metallic conical mirrors to laser applications. All the quality requirements to produce these mirrors were accomplished, but some difficulties were found when larger pieces were needed, because the system has some limitations. In order to improve the machined parts quality produced by the ultraprecision lathe, an effect evaluation and analysis was conducted to identify all the main errors sources and permit actions to be done to eliminate or attenuate theses errors sources. This analysis was based on vibration monitoring, where each machine system was tested and optimized to reduce the global vibration level to an acceptable level. All the procedures and results are shown, with a final comparison between machined parts before and after this evaluation and analysis.*

Keywords: *Ultraprecision machining, Vibration control, Machine tool design.*

1. Introduction

Ultraprecision machining is a research field where many factors must be taken in consideration for obtaining success in the quality of the machined components. And one of the factors that cause serious disturbances in the machining process is the existence of not controlled vibrations sources. Vibrations coming from the ground, generated in the proper machine or even though proceeding from sonorous noises can cause damages in the quality of the machined parts.

In this work the evaluation of diverse vibration sources effects allowed the optimization through the attenuation or even the elimination of these vibrations sources, which resulted in a significant improvement in the quality of the machined components. This evaluation had been carried through a methodology developed by Guimarães (2004a).

2. The ultraprecision lathe

The object of study of this work is an ultraprecision lathe located at Precision Engineering Laboratory from the Federal University of Santa Catarina. This machine assembly had begun with the acquisition of an ultraprecision lathe in disuse, that was dedicated to manufacture substrates for computer memory hard disks in 70`s. The main mechanical components of this lathe are the aerostatic bearing in the spindle and the base with high precision crossed guides, which make it adequate to use it in ultraprecision machining.

The lathe basis is constructed with casting iron, constituted of a Z-X table, and is composed of slipping prismatic guides. The lathe guides are known as "Double-V" guides and gives Z and X axles of the machine. As described by Moore (1970), the guides type “Double-V” provides a movement with excellent linearity, and according to Nakazawa (1994) it has zero play characteristics. On the other hand, slide guides present a phenomenon known as stick-slip and, due to this effect, it have limitations to work in high precision positioning applications, but it work fine in velocity controlled applications in ultraprecision.

The use of the machine in its original configuration was not possible due to documentation absence and to the obsolescence in its electronic components, which presented defects and it was not possible to find replacing parts. Another aggravation was the drive system of the main spindle. As the original spindle has big proportions, the inertia associated with its movement is also very high. It generates many difficulties in the drive, mainly in the movement deceleration. A system of brakes composed by a pneumatic circuit equipped the original machine, but it was considered dangerous to be used due to the high inertia of the spindle and the obsolescence of the brake system. Moreover, the original spindle drive had a maximum rotation of 2200 rpm, what was not sufficient for application requirements.

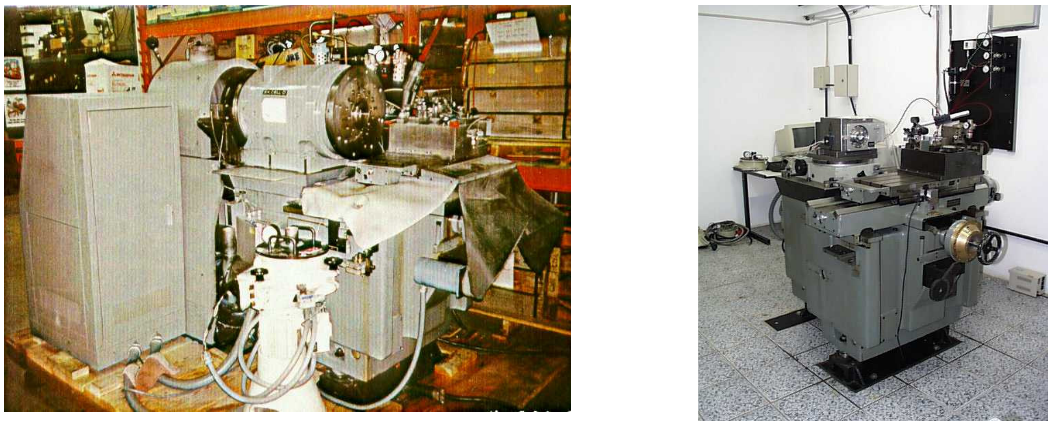


Figure 1. Original lathe conception and after retrofitting

Ahead of all difficulties to place the original lathe at work, many modifications in the lathe components were done to make it operational. These modifications had been helped by a design methodology developed by Pereira (2004). This design methodology is dedicated to reconfigurable precision and ultraprecision systems.

The most critical component of the original machine is the 14 counts diameter spindle, that presents many drive and control difficulties. Therefore, a Kugler module based on an aerostatic spindle and a brushless CC servomotor substituted the original headstock. Moreover, the substitution of the X table drive was necessary, to permit velocity controlled movement during ultraprecision machining. A step motor was chosen because it is a simple and low cost alternative. In Z axle, responsible for providing depth of cut in the machining process, manual drive was enough to permit the work conduction. This axle is only for positioning the tool and it doesn't demand integrated movement with the remaining portion of the machine. The Figure 1 shows the machine after the first stage of retrofitting, with the main alteration, the substitution of the lathe spindle.

With an analysis of the first retrofitting it became possible to conclude that the machine wasn't operating in the optimized way. Although it was possible to machine some good pieces, the global process repeatability was not good. During the empirical method used to get the best quality results, some limitations of the equipment had been identified. These limitations served as a starting point to get improvements in the results given by the machine:

- Inadequate drive - the step motor is not an ideal solution for precision systems, mainly for its characteristic of vibrations generation. Moreover, when the engine was working in the limit of its torque, what, in some cases is associated to the guides ineffective lubrication, it causes the motor to stall;
- Stick-slip - stick-slip influence is known as a influence factor over the quality of the pieces made, but it was not the aim of this study. It is possible to quantify its influence or to determine some standard procedure to optimize the use of these guides. A detailed study of this factor is described by Guimarães (2004b);
- Coolant application - the cooling fluid application and the chip removal generated a great disturbance in the system. This disturbance was evident and very significant, but it is possible to quantify it or to optimize its influence in the results;
- The aerostatic spindle presented pneumatic hammer phenomena for air supply pressure higher than 3 bar, what is totally harmful to the machining process. But it is possible to identify the excellent bearing band operation, causing the elimination of this effect and the stiffness optimization to the bearing;
- The spindle balancing was made only by the static method, which is inexact and forced the lathe operation to be done in the inferior cutting speed limits. A detailed and exclusive study of this factor is described by Guimarães (2005).

3 - Evaluation of the influence factors in the quality of the machined part

Starting from the list of limitations identified in the lathe, and also supported by the list of factors that influence in the machined parts quality in ultraprecision, presented by Schroeter (1997) and shown in figure 2, a list of parameters that must be monitored to optimize the machining process in the LMP lathe was generated:

1. Evaluation of the spindle dynamic balancing influence;
2. Evaluation of the cutting fluid injection system influence;
3. Evaluation of the chip removal system influence;
4. Evaluation of the vibrations sources coming from the environment and the ground influence;
5. Evaluation of the drive motor influence;

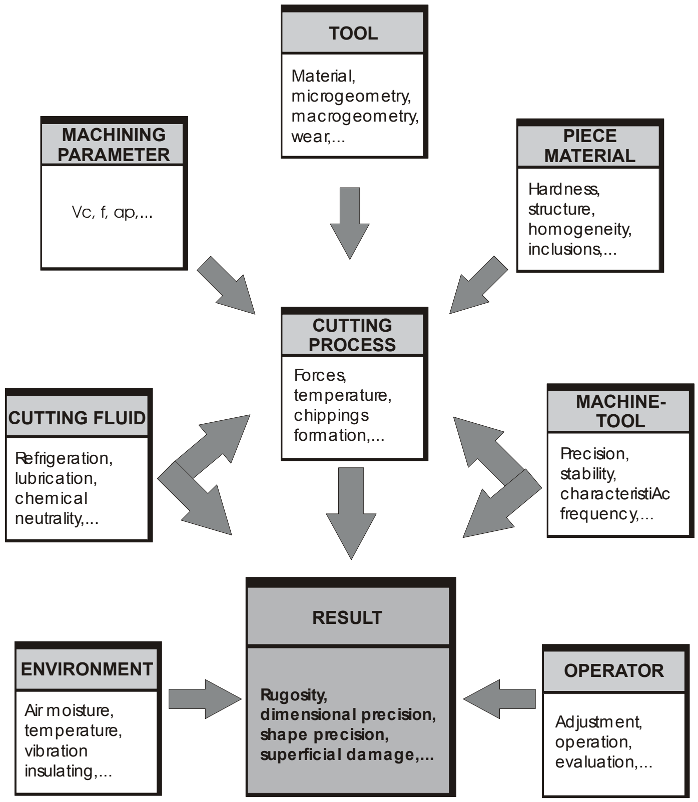


Figure 2. Factors that influence the quality of the ultraprecision machined parts (SCHROETER, 1997)

4 - Vibration monitoring System

In high precision machining small vibration amplitudes can affect the quality of machining surface. For this reason is very important to detect the vibration sources and act to minimize or eliminate them.

The methodology used to detect this source was based in the study of some factors that can have negative influence in the quality of machined surfaces. Using a machines diagnosis method described by Guimarães (2004a) and Carl Schenck AG. (1993a), experiments were done to minimize vibration effects for each source.

The developed methodology provides the realization of machine diagnostic, using some techniques of monitoring and automation. Carl Schenck AG. (1993b) brings information that assists the interpretation of the frequency spectrum graphics, as shown in table 1.

The experiments used consist in fixing accelerometers in different points of the machine, to permit monitoring in different situations. These signals were analyzed in time domain (peak-to-peak value) and in frequency domain, using the Fast Fourier Transformer (FFT). Through the evaluation of this graphics it's possible to verify the contribution of each influence factors.

The Precision Engineering Laboratory has one measurer of dynamic balancing, the *Schenck Vibrobalancer 41*, with one accelerometer of sensibility 100 mV/g. It can measure global vibration value (RMS, pick to pick, or only pick). The measurer electronic part cannot satisfy measurement requirements (low vibration amplitude measurements in time and frequency domain). Additionally it only shows values in time domain. Moreover, the update rates are not sufficient, hiding the transients that are important for study. As *Schenck* measurer update demands high costs, a new method was developed to analysis the frequency spectrum.

The next step was the specification of new accelerometers with adequate sensitivity. It is important to take care in the specification because accelerometers with relative big mass can modify the characteristic vibration of small objects.

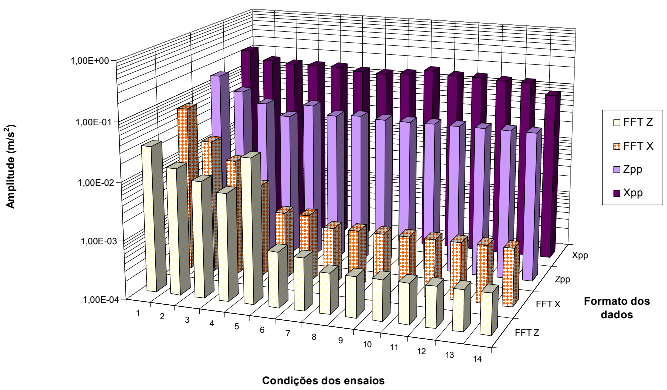
Chosen accelerometers were 352C18 and 355B03 from PCB Piezotronics, with a variable gain signal conditioner 480E09 (with gain of 1, 10 or 100 times). The signals treatment was developed with Labview® software.

TABLE 1 – Vibrations identification table (CARL SCHENCK A.G., 1993b)

Vibration source		**Vibration related frequencies**									
		0-40% f_{Rotor}	40-50% f_{Rotor}	50-100% f_{Rotor}	f_{Rotor}	2x f_{Rotor}	Entire multiples of f_{Rotor}	Diverse frequencies	High frequencies	1 or 2x source frequencies	1 or 2x belt frequencies
Balancing	Non uniform mass distribution in rotating elements				●	○	○				
Alignment error distorcion	Alignment error				●	●	○				
	Base strain		○		●	○	○				
	Carcass distortion	○	○	○	●	○					
	Axial contact of rotor	○	○	○	●	○	○	○	○	○	○
Defective bearing and skin bearing non round	Defective roll element				○			●	○		
	Damaged bearing	●	●	●	●	●					
	Eccentricity of bearing and skin				●	○					
Electricals and Magnetics disturbances	Asymmetrical stator									●	
	Asymmetrical rotor	●									
	Eccentric magnetic gap	It depends of constructions characteristics									
Drive for defective belt	Non uniform belt section							○			●
Resonance	Of skins, foundation and constructive elements	It can occur in a large spectrum of frequency									
	Critical speed of rotor or rotor/bearing system				●						
Aerodinamic and hydraulic forces					○		●		○		
Instability	Oil displacement		●								
	Oil injection		●	○							
	Forced excitation	●	○	○							
	Excitation by magnetic forces	○	●	○							
Gear and coupling	Gear error						○	○	●		
	Damaged coupling		○		○	○	●				
Vibrations transmitted by near machines		It can occur in a large spectrum of frequency									
		● = Characteristic vibration frequency ○ = Vibration frequency that can occur in a different place from the characteristic vibration frequency									

5 –Results

Many experiments were made using accelerometers and vibration analysis program. These experiments showed the contribution of each part of the machine in different operation conditions and, with a comparative method the worst factor of influence could be detected. After this analysis, a machine global vision was possible. The figure 3 shows the experiments results with vibration head unbalancing variations.

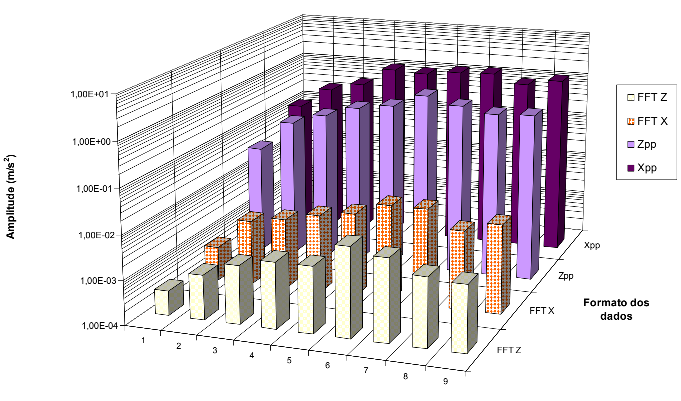


Test	Parameters	Fixture
1	8000rpm, 250mg unbalanced	Spindle
2	7000rpm, 250mg unbalanced	Spindle
3	6000rpm, 250mg unbalanced	Spindle
4	5000rpm, 250mg unbalanced	Spindle
5	4000rpm, 250mg unbalanced	Spindle
6	3000rpm, 250mg unbalanced	Spindle
7	2200rpm, 250mg unbalanced	Spindle
8	8000rpm, balanced	Spindle
9	7000rpm, balanced	Spindle
10	6000rpm, balanced	Spindle
11	5000rpm, balanced	Spindle
12	4000rpm, balanced	Spindle
13	3000rpm, balanced	Spindle
14	2200rpm, balanced	Spindle

Figure 3. Results from unbalancing experiments (GUIMARÃES, 2004a)

Figure 3 shows the importance of a good balancing in high precision machining. A small unbalancing amplitude value can become a big source of vibration, harming the machined piece quality. The figure 3 shows that when a good balancing was applied the vibration level decreased.

On figure 4, experiments were done with variations in nozzle position from cutting fluid injection system, monitoring the vibrations in the spindle and in the cutting tool.



Test	Parameters	Fixture
1	Free accelerometers, all off	Free
2	Fluid at tool edge, spindle off	Spindle
3	Fluid at tool face, spindle off	Spindle
4	Fluid at tool edge, spindle off	Tool
5	Fluid at tool face, spindle off	Tool
6	Fluid at tool edge and piece	Tool
7	Fluid at tool face and piece	Tool
8	Fluid at tool edge and piece	Spindle
9	Fluid at tool face and piece	Spindle

Figure 4. Results from cutting fluid injection experiments (GUIMARÃES, 2004a)

It is possible to identify significant vibration variations in different cutting fluid nozzle positions. Comparing the measurements values with the static machine condition (Test 1 of figure 4) is possible to see the importance of this parameter.

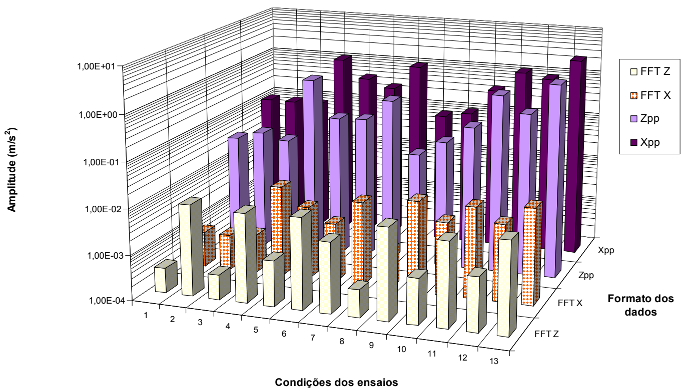
In figure 5, the chip removal system was tested in different positions.

These experiments show important results about de vibration source caused by sound effect. The chip removal system is sucked in an adapted domestic aspirator. This equipment produce a high level of noise, and for this reason, experiences were made with the aspirator inside and outside of the room. The figure shows the importance of the nozzle position in the ultraprecision machining process.

Figure 6 shows two types of drive motors used to movement the main lathe guide. The step motor and the CC brushless motor were compared. As expected, CC brushless motor is better for this application.

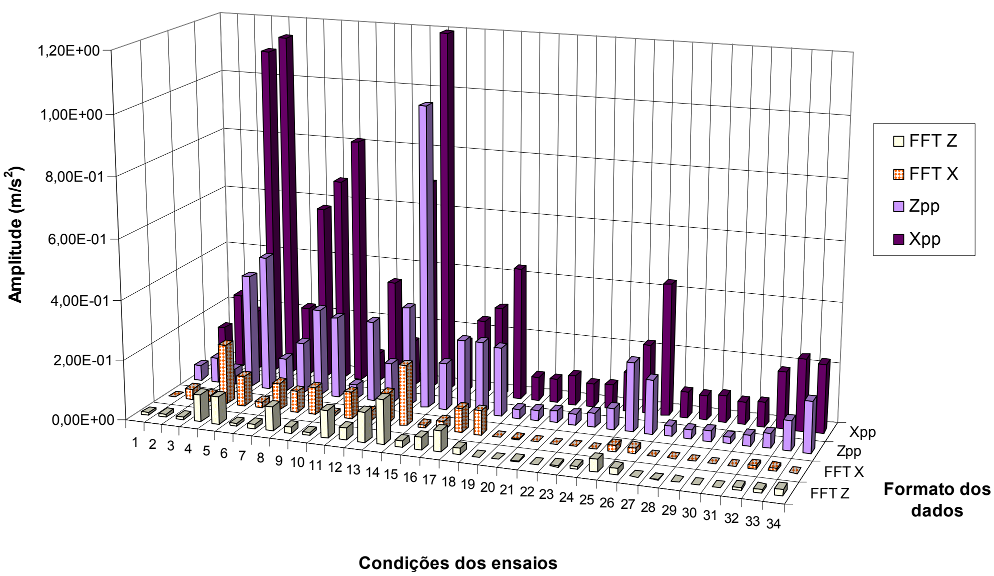
Caution must be done to operate in optimized travel speed range. Even using the best motor solution, in some speed values the vibration levels are high enough to influence the machining quality.

The vibration response tests were done also with sensors fixture in tool place and in the spindle, which are the main positions to define final machining quality.



Test	Parameters	Fixture
1	Free accelerometers, all off	Free
2	Out of room, open door	Tool
3	Out of room, closed door	Tool
4	Chip removal at tool face	Tool
5	Chip removal at tool edge	Tool
6	Chip removal at tool edge	Spindle
7	Chip removal at tool face	Spindle
8	Out of room, closed door	Spindle
9	Out of room, open door	Spindle
10	Removal at tool edge and piece	Spindle
11	Removal at tool face and piece	Spindle
12	Removal at tool edge and piece	Tool
13	Removal at tool face and piece	Tool

Figure 5. Results from chip aspiration experiments (GUIMARÃES, 2004a)



Test	Parameters	Fixture	Test	Parameters	Fixture
1	Step motor, 5mm/min	Tool	18	Step motor, 100mm/min	Spindle
2	Step motor, 10mm/min	Tool	19	CC, 5mm/min	Spindle
3	Step motor, 15mm/min	Tool	20	CC, 10mm/min	Spindle
4	Step motor, 20mm/min	Tool	21	CC, 15mm/min	Spindle
5	Step motor, 21mm/min	Tool	22	CC, 20mm/min	Spindle
6	Step motor, 25mm/min	Tool	23	CC, 25mm/min	Spindle
7	Step motor, 50mm/min	Tool	24	CC, 50mm/min	Spindle
8	Step motor, 75mm/min	Tool	25	CC, 75mm/min	Spindle
9	Step motor, 100mm/min	Tool	26	CC, 100mm/min	Spindle
10	Step motor, 5mm/min	Tool	27	CC, 5mm/min	Tool
11	Step motor, 10mm/min	Spindle	28	CC, 10mm/min	Tool
12	Step motor, 15mm/min	Spindle	29	CC, 15mm/min	Tool
13	Step motor, 20mm/min	Spindle	30	CC, 20mm/min	Tool
14	Step motor, 21mm/min	Spindle	31	CC, 25mm/min	Tool
15	Step motor, 25mm/min	Spindle	32	CC, 50mm/min	Tool
16	Step motor, 50mm/min	Spindle	33	CC, 75mm/min	Tool
17	Step motor, 75mm/min	Spindle	34	CC, 100mm/min	Tool

Figure 6. . Results from drive engine influence experiments (GUIMARÃES, 2004a)

Figure 7 shows the machining final results after the optimization of appraise aspects of lathe. The shown piece could not be machined with the adjusted quality using the lathe with the previous configuration. Quantitative values of form and surface quality could not be measured because there was no adequate equipment to do it. Conclusions must be done in a qualitative way, due to the absence of an adequate surface roughness measurer.

Figure 7. Machined part after the lathe optimization

6 – Conclusions

The mounted experimental apparatus performed efficient and valuable information about the ultraprecision machining process and its sources of disturbance. The main vibration sources were well measured and controlled, given the shown result.

The machined part quality can be attested by its application in a measurement optical device. The part consists in an external conical mirror with a diameter of 80 mm and 40 mm of height. It has the function of reflecting a perimeter image to compose a planar vision of a cylinder area as a disk format. This reflection must have most possible fidelity, with no distortions. The mirror quality could be assured by the measurement device performance, with clear and precise images. This part dimension could not be machined in the previous lathe configuration.

To each new needed component, and with a new lathe configuration, previous tests can be done to assure lower vibration levels, making possible to extract best machine performance.

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