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CONTRIBUTION CONCERNING MACHINE-TOOL ACCURACY USING SOFTWARE METHODS FOR GEOMETRICAL ERRORS COMPENSATION

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Abstract: *The paper presents a possibility to reduce the errors of high speed machine tools by changing CAD and CAM models according with linear and angular errors on each axis. The geometrical errors were measured with LASER interferometer and used into homogeneous transformation matrix. A C++ software was developed to generate CATIA V5 files for ideal, real and compensation surfaces, curves or points.*

Key words: *high speed machining, LASER interferometer, linear and angular errors, CAD-CAM compensation.*

1. INTRODUCTION

High speed machining (HSM) is a key which enables technology to be used in an increasing number of industries. In the aerospace industry, structural components are increasingly being machined as monolithic structures from a single billet. The results are drastically reduced part counts, assembly costs, and even maintenance costs. The Boeing F/A 18 E/F tactical aircraft realized a 42% reduction in parts and a 25% weight savings over previous models. The design changes made practical by the application of high speed machining technology have a big share in this. In the tooling industry, high speed machining technology continues to grow important for maintaining economic competitiveness. Successful applications of HSM to the production of tooling for forging, extrusion, sheet forming, die casting, and injection moulding have been reported.

High-velocity (HV) machine tools with 1,000 + ipm traverse rates, and 50,000 + RPM high-power spindles, are readily available. However, the velocity capabilities of such machines are seldom reached in industrial practice. Often, conservative feedrates are employed in contouring due to concerns arising from process stability and acceleration limitations. To address these issues, significant attention has been focused on the important problems of dynamic modelling, parameter optimization, and feedrate scheduling. Often overlooked, however, is the potential for improvement in process efficiency through changes to the tool-path itself. Tool-path planning has been traditionally approached from a purely geometric perspective. The vast majority of bulk material removal occurs in 2.5D roughing operations. For such operations, toolpath trajectories are generated through conventional strategies, such as contour-parallel or direction-parallel offsetting. When the dynamics and mechanics of the process and machine tool system are considered, conventional tool-path generation techniques are observed to be far from ideal.

In the present paper, an approach is developed to optimize NC programs by implementing the machine tools errors on each axis into algorithm. Therefore, the CAD (Computer Aided Design) systems can generate optimized surfaces based on real and ideal pieces surfaces for CAM (Computer Aided Manufacturing) advanced systems.

2. MACHINE TOOLS ERRORS

Numerous error origins affect tool tip position. Among the key factors that affect the accuracy of this relative position are the geometric errors of the machine tool and thermal effects on the machine tool axes. Other error origins are the resolution and accuracy of the linear measuring system, elastic deformation of drive components, inertia forces when braking/accelerating, friction and stick slip motion, the servo control system and cutting force and vibration [2].

For a multi-axis machine, the calibration should include each axis and its roll, pitch, yaw, squareness and positioning error in the workspace. The static working load and the mass of the workpiece being machined produce distortions that result in positioning errors in the machine tools.

In general, CNC machine tool inaccuracy is caused by:

- geometric errors of machine components and structures,
- errors induced by thermal distortions,
- friction in drive system,
- deflection caused by cutting force,
- servo control system,
- random vibration.

The following Fig. 1 shows the error origins of multi-axis machine tools and their high level relationships. Broadly, machine tools errors can be divided into two categories: systematic errors and random errors. Systematic errors can be described and are predictable based on some mathematical models. Random errors are difficult to model and to compensate.

Systematic errors are those, which we are able to describe and predict their amount in machine tools workspaces. On the other hand, random errors are difficult and complex to describe [3].

Geometric errors are often met in systematic errors and the predominant origins are ball screws, guideways, bearings etc. Ball screw pitch error, inaccurate production,

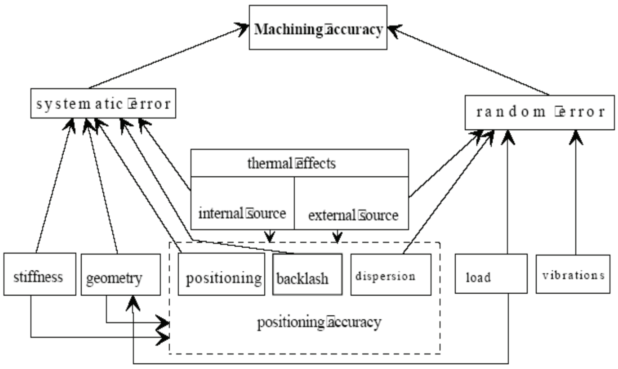


Fig. 1. Total error sources of machine tools (Anderson 1992).

wear in guideways etc. are factors that contribute to geometric error. Geometric error has good repeatability and changes gradually with time. A machine tool operates also in non steady state due to thermal distortions. Different parts of machine tools are deformed based on thermal flux. There are two major kinds of heat sources for machine tools: external (ex: room temperature, sun rays etc.), and internal, which are generated by internal friction among different components of the machine. Uneven dynamic characteristics will lead to the generation of vibrations. There are two kinds of vibrations: self excited vibration and externally excited vibrations. The control system and measuring system of the machine itself affects positioning error. For semi closed loop type there is no direct measuring system whereas for a closed loop there is a direct measuring system.

3. ERRORS MODELLING ON MACHINE TOOLS

Most machine tools are designed with the intention that all of the joints will be either prismatic or rotary (for more than 3 axis machine tool), but it is physically impossible to construct a joint that will perfectly generate this type of motion. This type of error always exists, but because of the servo tuning and calibration process, these errors are taken into consideration in CNC controllers. For example, most prismatic joints consist of a carriage constrained to move along a bar. Since the bar will be subject to some slight curvature or irregularities along its surface, the generated motion will not be pure prismatic as expected. These irregularities will create Roll, Pitch and Yaw (RPY) error while moving with nominal movement. Even if the movements were perfect, as with new machine tools, in time it will start to create RPY [2]. Always the ideal tool tip position is located based on machines' geometric and/or thermal information. While calculating the tool tip location based on ideal geometry and generating corresponding servo commands for the ideal position in a Cartesian coordinate system, the machine will position the tool tip to a different location due to geometric and other errors.

The real position of tool tip in space will be translated and rotated after each axis of Cartesian systems like in Fig. 2. The tool tip position will be translated on *X* with x_r (cumulated machine tool linear errors on *X* axis), on *Y* with y_r (cumulated machine tool linear errors on *Y* axis),

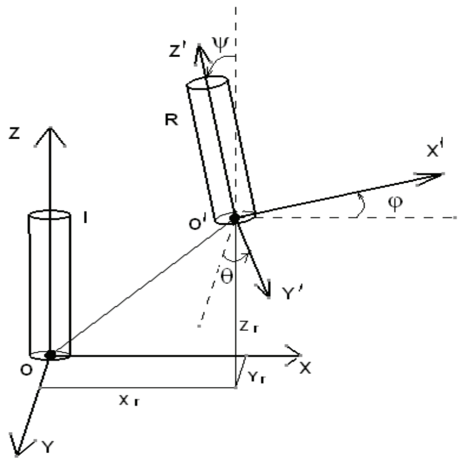


Fig. 2. Ideal and real tool tip position.

on *Z* with z_r (cumulated machine tool linear errors on *Z* axis) and rotated with Ø (cumulated machine tool angular errors on *X* axis), with ö (cumulated machine tool angular errors on *Y* axis) and with è (cumulated machine tool angular errors on *Z* axis). In reality this position can not be measured by machine tools command system so it can not be corrected [2].

For transformation from Cartesian system *OXYZ* into Cartesian system $O'X'Y'Z'$ the next homogeneous transformation matrixes were used:

$$T_r = \begin{bmatrix} r_x \\ r_y \\ r_z \end{bmatrix} \tag{1}$$

$$R_{Rx=} \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$R_{Ry} = \begin{bmatrix} \cos\varphi & 0 & \sin\varphi \\ 0 & 1 & 0 \\ -\sin\varphi & 0 & \cos\varphi \end{bmatrix} \tag{3}$$

$$R_{Rz} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix}. \tag{4}$$

The transformation vector from point O to point O' I results as:

$$T_{OO'} = R_x \cdot R_y \cdot R_z \cdot T_r. \tag{5}$$

The result of this calculus was implemented into C++ software which generates automatically ideal, real and compensation surfaces, curves or points for *xy* plan.

$$T_{OO'} = \begin{bmatrix} (\cos\psi\cdot\cos\varphi - \sin\psi\cdot\cos\theta\cdot\sin\varphi)\cdot r_x + \\ +(\cos\varphi\cdot\sin\varphi + \sin\psi\cdot\cos\theta\cdot\cos\varphi)\cdot r_y + \\ +\sin\psi\cdot\sin\theta\cdot r_z \\ (\sin\psi\cdot\cos\varphi + \cos\psi\cdot\cos\theta\cdot\sin\varphi)\cdot r_x - \\ -(\sin\psi\cdot\sin\varphi - \cos\psi\cdot\cos\theta\cdot\cos\varphi)\cdot r_y - \\ -\cos\psi\cdot\sin\theta\cdot r_z \\ \sin\theta\cdot\sin\varphi\cdot r_x + \sin\theta\cdot\cos\varphi\cdot r_y + \cos\theta\cdot r_z \end{bmatrix} \tag{6}$$

The C++ software takes into account the geometrical errors (linear and angular) measured with a RENISHAW LASER Interferometer.

The errors generated by other factors can also be easily introduced into calculus [3].

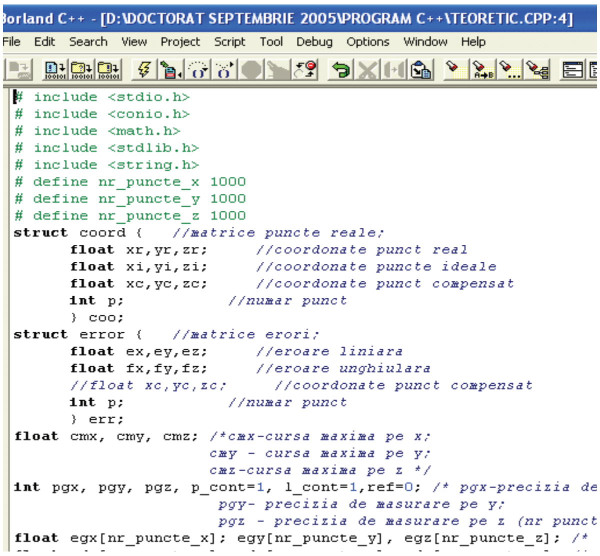
The generated elements are used to change CAD and CAM model. This software generates directly CATIA script files (Fig. 4) for the studied surfaces and allows modifying them very easily depending on the errors in each measured points. Three CATIA files **ideal.catscript, real.catscript,** and **compensat.catscript** are automatically generated.

The main idea of this software is to generate and use compensate surface of real surfaces based on machine measured errors in normal working state (temperature, vibration, etc).

Based on this compensate surface an NC program should be generated for high speed surface machining. The compensate errors plus machine tool errors should be nearly 0 (ideal machine tool).

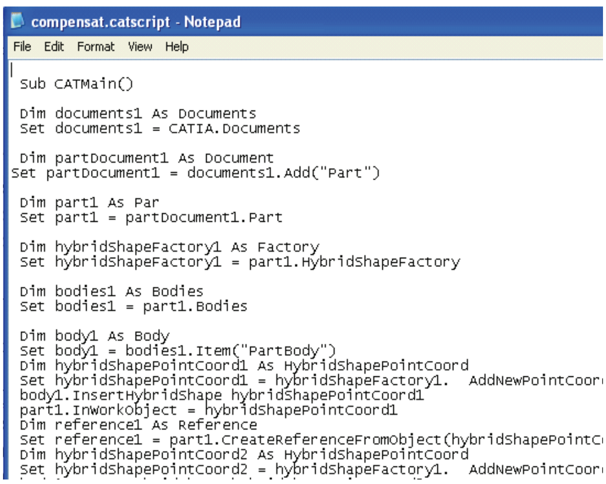
4. STUDY CASE

A practical research was made on a Gantry machine tool with high speed feed rate.



```
Borland C++ - [D:\DOCTORAT SEPTEMBRIE 2005\PROGRAM C++\TEORETIC.CPP:4]
File Edit Search View Project Script Tool Debug Options Window Help
# include <stdio.h>
# include <conio.h>
# include <math.h>
# include <stdlib.h>
# include <string.h>
# define nr_puncte_x 1000
# define nr_puncte_y 1000
# define nr_puncte_z 1000
struct coord {    //matrice puncte reale;
       float xr,yr,zr;     //coordonate punct real
       float xi,yi,zi;     //coordonate puncte ideale
       float xc,yc,zc;     //coordonate punct compensat
       int p;           //numar punct
       } coo;
struct error {    //matrice erori;
       float ex,ey,ez;     //eroare liniara
       float fx,fy,fz;     //eroare unghiulara
       //float xc,yc,zc;     //coordonate punct compensat
       int p;           //numar punct
       } err;
float cmx, cmy, cmz; /*cmx-cursa maxima pe x;
                     cmy - cursa maxima pe y;
                     cmz-cursa maxima pe z */
int pgx, pgy, pgz, p_cont=1, l_cont=1,ref=0; /* pgx-precizia de
                      pgy- precizia de masurare pe y;
                      pgz - precizia de masurare pe z (nr punct
float egx[nr_puncte_x]; egy[nr_puncte_y], egz[nr_puncte_z]; /*
```

Fig. 3. Image of C++ compensation software.



```
compensat.catscript - Notepad
File Edit Format View Help
Sub CATMain()

Dim documents1 As Documents
Set documents1 = CATIA.Documents

Dim partDocument1 As Document
Set partDocument1 = documents1.Add("Part")

Dim part1 As Par
Set part1 = partDocument1.Part

Dim hybridShapeFactory1 As Factory
Set hybridShapeFactory1 = part1.HybridShapeFactory

Dim bodies1 As Bodies
Set bodies1 = part1.Bodies

Dim body1 As Body
Set body1 = bodies1.Item("PartBody")
Dim hybridShapePointCoord1 As HybridShapePointCoord
Set hybridShapePointCoord1 = hybridShapeFactory1.  AddNewPointCoor
body1.InsertHybridShape hybridShapePointCoord1
part1.InWorkObject = hybridShapePointCoord1
Dim reference1 As Reference
Set reference1 = part1.CreateReferenceFromObject(hybridShapePointC
Dim hybridShapePointCoord2 As HybridShapePointCoord
Set hybridShapePointCoord2 = hybridShapeFactory1.  AddNewPointCoor
```

Fig. 4. Image of compenst.catscript generated file.

The FAV 3300 portal milling machine with overhead gantry is based on a modular machine concept, which permits construction of a wide variety of versions with different travels and drive technologies. The FAV 3 300 is designed for the high speed machining of the whole range of materials, right through to HSC roughing of cast iron and steel. The machine concept is rigorously optimized for maximum rigidity and dynamic performance.

The milling machine [2] tool has a linear movement up to 5 500 mm on *X* axis, 3 300 mm on *Y* axis and 2 300 on *Z* axis with maximum 15 000 mm/min. The movement on the *X* direction is made by using a rack mechanism with error compensation system and linear guides NSK with mechanism for parallelism error compensation. The movement on y direction is made by using a ball screw with double ball nuts. Also are used NSK linear guides. In Fig. 5 is presented the FAV 3300 Gantry Machine. The machine precision is up to maximum 20 micrometers in hard work condition [5].

The geometrical and dynamical errors were measured with a REINSHAW ML10 LASER Interferometer and a Brüel & Kjær Vibroport 41 (from National Centre of Research of the Technological Systems Performances) according with the machine tool producer specification for each axis with 100 mm steps.

The angular and linear geometrical errors were measured for the tool tip point (the LASER mirrors were mounted on the milling head – Fig. 5 [5]).

After these measures an errors spectrum of the FAV 3 300 machine tools was obtained [1].

In Fig. 6 it is presented some linear errors measured with ML10 LASER for *X* axis in 56 points (*X* axis has 5 600 mm).

In Fig. 7 a frequency spectrum measured with Vibroport 41 is presented.

The result of this kind of measures was introduced into C++ software (Fig. 3). All the tree surfaces (ideal, real and compensate) were generated based on the errors calculus algorithm.

In Figs. 8 and 9 it is presented an ideal plan and the real and compensates surfaces. The compensated surfaces were used to generate NC manufacturing programs.

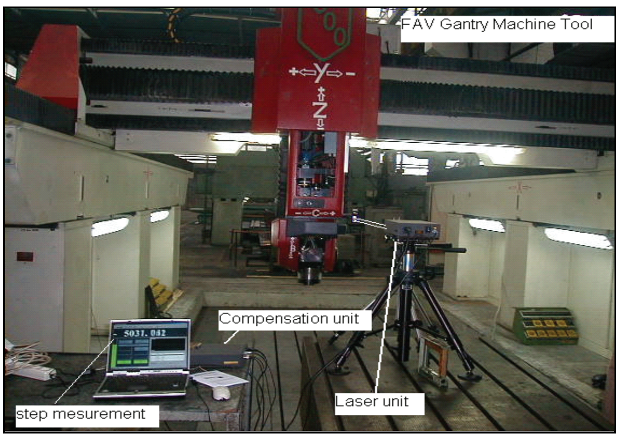


Fig. 5. Gantry Machine Tool and ML10 LASER interferometer.

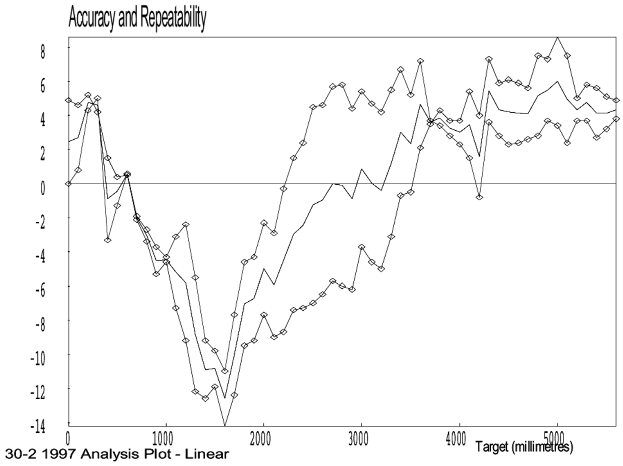


Fig. 6. Linear errors on X axis.

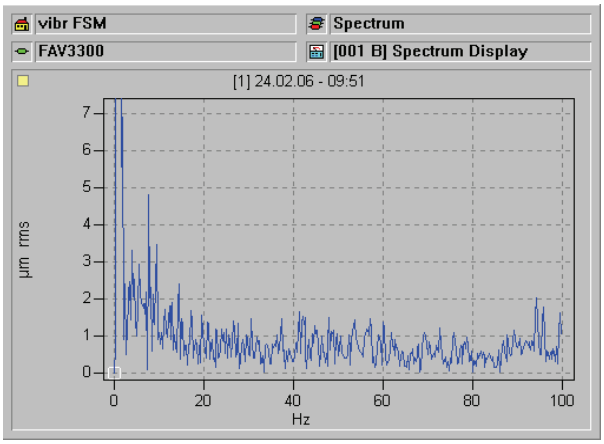


Fig. 7. Frequency spectrum.

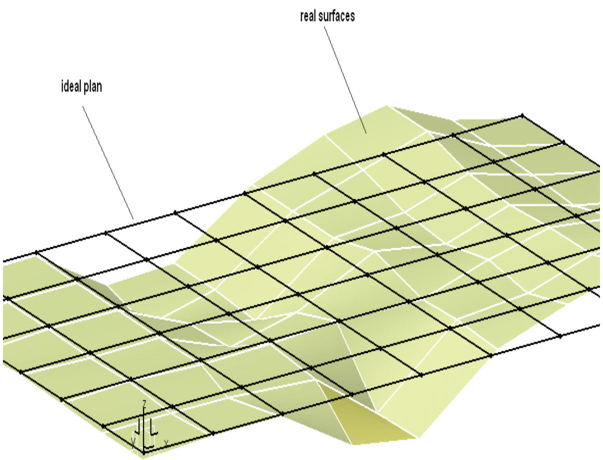


Fig. 8. Ideal and real surfaces.

5. CONCLUSIONS

The solution that we proposed in this paper has the advantage of making a CAD correction, function of the machine tool cumulated errors.

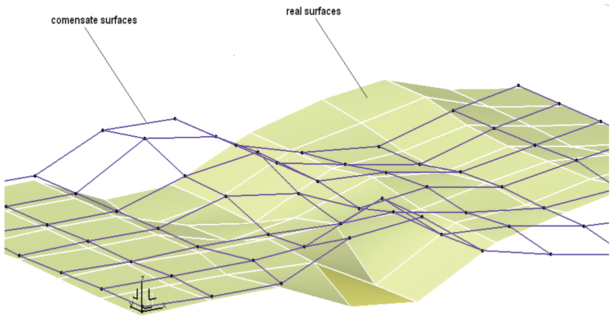


Fig. 9. Real and compensate surfaces.

The NC programs will be generated on the compensate surfaces and, as a result, the machine tool accuracy errors plus compensate errors from NC program shall be nearly “0”.

The errors correction is not depending of machine tool CNC system or the machine tool measuring systems. It can be easy implemented on all type of machine tool, even for the high speed. The errors values used for calculus were measured with high precision instrument (LASER Interferometer, Vibroport 41 etc), independently from the machine tools. These are errors that machine tools systems can not monitored.

Machine tools are very complex in nature with their functionality. Due to wear, the errors will change in time. Machine tools calibration with a long period of time shows that a calibration period of one year is advisable.

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