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Practical Results in Volumetric Compensation using VCS

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Abstract

The actual machine tool market is always more demanding in performance especially for large dimensions machine. One grate help to obtain better quality results is done by electronic compensation, that in the last years evolved from the compensation of some of the largest sources of error to consider all the machine volume, in those terms the compensation is called Volumetric Compensation. Modern approach is to take in consideration all the 21 degree of freedom in generating the compensation tables and measure the machine performances using diagonal measurements as described by ISO 230-6 or ASME B5.54 standards. Reported are the basic theory and volumetric compensation methods, the description of a new approach using only two type of last generation laser instruments, a laser interferferometer and a 3 perpendicular planes scanning laser. The method of measurement for data collection and for the verification are described and the data results reported for two different application in aerospace.

1 Volumetric Compensation Description

The more often used mathematical models for the Volumetric Error study in serial kinematics are the Rigid-body and the Nonrigid-body that take in consideration the movement of the masses. The Rigid-body model in a 3 axes machine with 3 Cartesian axis in a serial kinematics design, is the one where the X- Y- and Z- axes are orthogonal and are stacking on each other, takes in consideration the 21 classic degree of freedom that are: 3 linear errors (positioning in X, Y and Z), 6 straightness errors (lateral and vertical deviation for the 3 axes), 3 angular errors (pitch, roll and yaw for each axis) and 3 perpendicular errors of the 3 Cartesian axes, for a total of 21 errors. The mathematical model and the measurement are relatively simply but the SAG (deformation) errors are not taken in consideration. The compensation in this case is performed measuring all the 21 degree of freedom, and every axis is measured in the center of the machine only. The CNC for every positioning, calculate the new position coordinates taking in consideration the possible errors, both linear and angular in the new position and correct the positioning accordingly. One alternative method that it is able to correct the Nonrigid-body errors, is based on a matrix of points inside the volume.

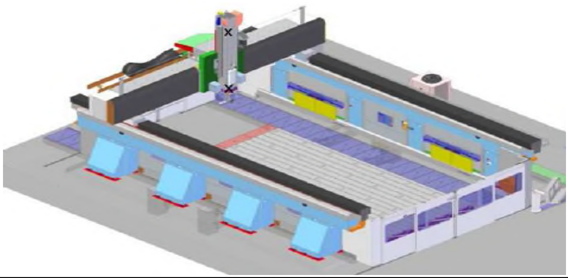


fig.1 Machine that was volumetrically

For each one of those points the positioning deviation in X, Y and Z is measured. The method it is conceptually simple, but the difficulty is in the practical impossibility, with the actually available instrumentation, of measure with the necessary accuracy, points arbitrarily positioned in the space. The following example of compensation is referred to the Rigid-body and are described measurements performed with 1- Optodyne laser interferometer for the 3 linear positioning and 4 diagonal verification measurements and 2- Hamarlaser scanning laser for the geometrical measurement: 6 vertical and horizontal straightness, 9 angles (pitch, roll and yaw for each of the 3 Cartesian axes), and 3 squareness. Total 21 errors.

The machine tools performances, in terms of accuracy, are determined by the 3D or volumetric accuracy, that includes positioning errors, straightness errors, angular errors and errors generated by temperature. the volumetric accuracy V(XYZ) it is the maximum deviation between the actual position and the theoretical position in X, Y and Z and the orientation in ABC for movements in the concerned volume. The body diagonal displacement as defined in the ISO230-6 o ASME B5.54 standards it is a good quick check of the volumetric error. All the machine errors contributes to the error on the 4 diagonals, hence to measure the accuracy on the 4 diagonals define the volumetric accuracy including the squareness.

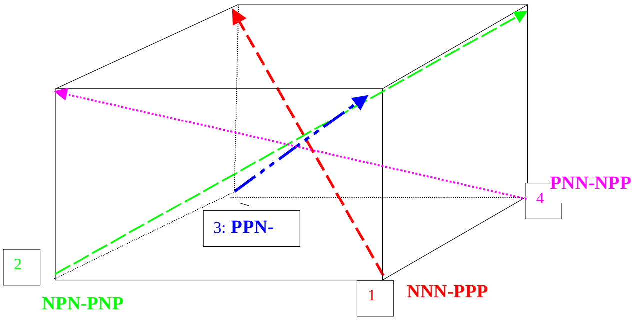


fig.2 The 4 diagonals measurement in the working volume

The measurement of the accuracy of the diagonals allow to verification of the sum of all the machine errors, but it is not possible to define the contribute of each single error with exclusion of squareness. The squareness is calculated starting from the difference of the diagonal value versus the nominal values.

2 Proposed evaluation method

A machine tools is normally specified with values defined generically in the ISO-230-1 or to the specific standard for each machine type. The values for the

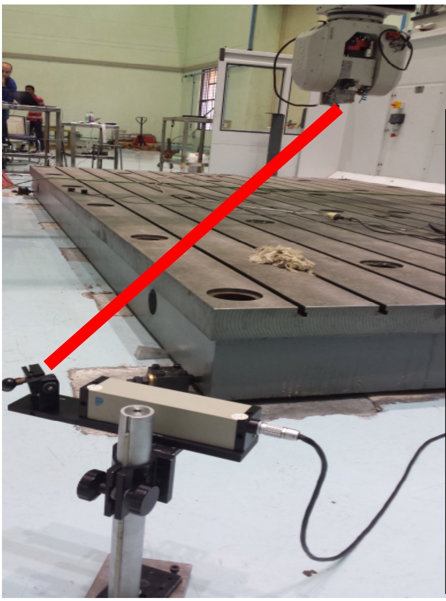


fig.3 Volumetric diagonal test .

The laser beam is shouted to the diagonal and the machine is moving along the diagonal moving all the 3 axis at the same time. All the machine errors are contributing to the positioning errors along the diagonal.

test book are defined by the measurement of the values on each singular axis and in the center of machine, but how to connect those values to the volumetric error ? We offer to discussion this possible simplified solution. Considering that the 21 error used in the error volumetric error calculation are not totally independent, but are connected by angular errors, hence we define the square of the volumetric error the quadratic sum of the 12 error that we can consider independents 3 position, 6 straightness and 3 squareness.

$$V(xyz)=\sqrt{Exx)^2+(Eyy)^2+(Ezz)^2+(Eyx)^2+(Ezx)^2+(Exy)^2+(Ezy)^2+(Exz)^2+(Eyz)^2+(SQRxy)^2+(\ SQRxz)^2+(\ SQRzy)^2}$$

To have an idea of the comparison between linear accuracy and volumetric accuracy we propose the following simplification: pose the hypothetic case that every error is equal to 1, than

$$V(xyz)=\sqrt{1^2+1^2+1^2+1^2+1^2+1^2+1^2+1^2+1^2+1^2+1^2+1^2}=\sqrt{12}=3.46$$

Thinking to the volumetric error, we have to imagine the Volumetric error values at least 3 times lager than the average of linear axes errors.

Taking the linear error values from a test book of a real machine with axis of 6000 X 4000 X 1800mm we can calculate the expected volumetric error.

$$V(xyz)=\sqrt{0.02^2+0.01^2+0.015^2+0.06^2+0.04^2+0.02^2+0.06^2+0.04^2+0.02^2+0.03^2+0.03^2+0.03^2}=$$

$$= 87\ \mu m\ \ o\ 13\ \mu m/m$$

The systems put at our disposition from the CNC manufacturers, in order to perform in easy way the volumetric compensation are practically only two, 3D Rotary from Fanuc e VCS (Volumetric Compensation System) from Siemens, the first it is based on a matrix of points in the volume and the second is based on separate data for each error on each axis. In this article we will describe the compensation performed with the VCS system, will be also described how to collect accurately and in short time all the errors with only two laser instruments type, one for linear and diagonal displacement and the second for all the geometry values.

The sequence of the measurements was the following:

1- Angular and straightness errors with introduction of the comp tables for the angular and straightness errors.

2- Measurement of Linear position errors at the center of travel for each axis and error correction.

3- Volumetric diagonal errors measurement.
The volumetric measurement was performed with active VCS correction tables and without correction tables in order to evaluate the accuracy improvement.

Both the linear position errors and the diagonal position errors was measured with a laser interferometer Optodyne MCV500, the big advantage using this new technology interferometer is that is not necessary an intermediate optics between laser head and retroreflector, it allow easy and fast alignment even shouting the laser beam in diagonal.

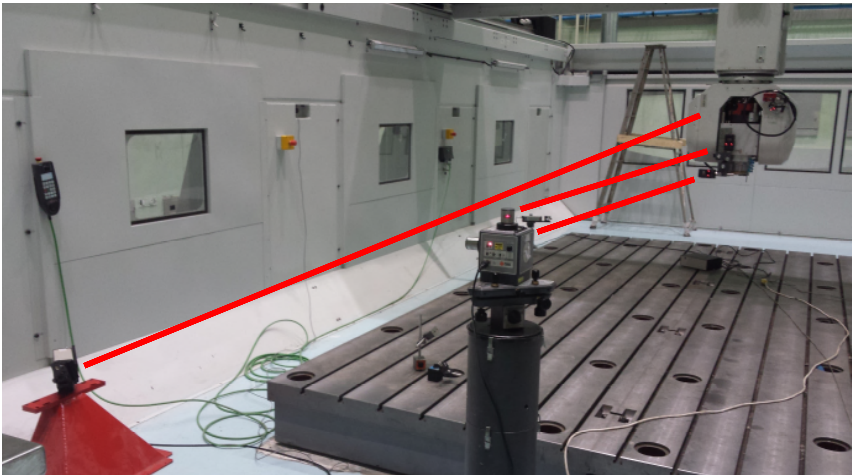


fig.4 Straightness with Hamarlaser L-743scanning laser and (in the left corner) laser Optodyne MCV 500 for diagonal measurement, ready for

Angular and straightness error was performed using a scanning laser Hamarlaser L-743 with 3 light planes diffused for 30m and mutually perpendicular. The laser beam illuminate the sensors that are positioned on the machine head. Both the sensors are measuring the straightness but in different position of the head, the average of the two reading represent the straightness and the difference the rotation angle. The difference of the two measurement expressed in mm divided by the distance from the two sensors expressed in meter represent the angle expressed in milli-radiants or mm/m. To simplifier the description the sensors are shown in couples in order to define a specific measurement. Two sensors positioned frontally side by side are measuring vertical straightness and Roll angle, two sensors positioned vertically on the side of the head are measuring vertical straightness and Pitch angle, two sensors positioned horizontally on the side of the head measure the horizontal straightness and the Yaw angle.

In the practical application in order to speed-up measurement operations, a quantity of 5 sensors for the scanning laser and also the retroreflector for the interferometer are mounted at the same time directly on the head or on a convenient support, in order to measure all the degree of freedom related to on axis at the same time in a single pass. The errors are: positioning, horizontal and vertical straightness, Pitch, Roll and Yaw angles.

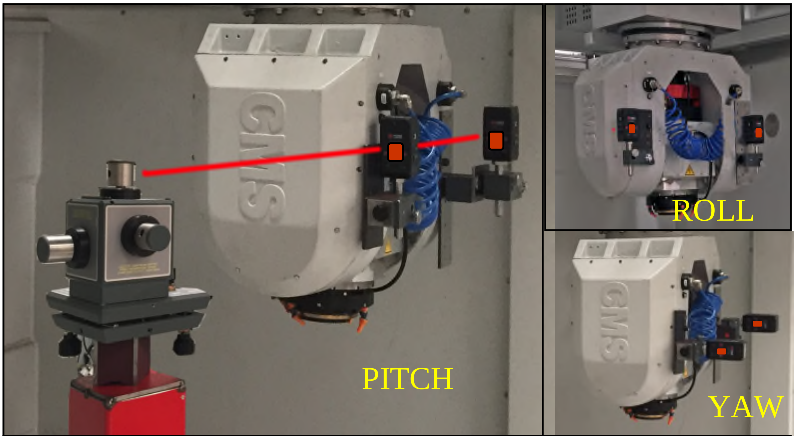
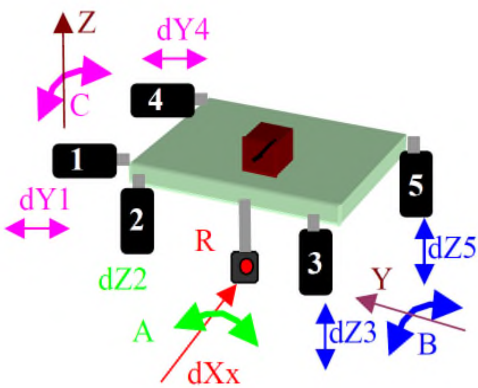


fig.5 Straightness and angular measurements. In the large picture the laser that emit the reference planes and two sensors for the vertical straightness measurement and Pitch angle. In the small upper picture the Roll angle measurement and in the lower the measurement of horizontal straightness and Yaw angle.

Temperature it is a crucial point in measurement and temperature variation it is the highest disturb is the temperature variation. It is necessary to keep temperature as stable is possible and/or increase the speed in data collection. Was used Hamarlaser because you can collect straightness and angular error at the same time and it is the same instrument was used to build up the machine. Optodyne interferometer with coaxial beam was crucial for linear and diagonal measurement. The time necessary for collecting the data for the 3 axis machine with 7.5 m in the longer axis is less than one day and one more day for the diagonal measurements and final checking.

Description of the measurement performed by the synergy of Hamarlaser L-743 and the Optodyne MCV-500 single beam interferometer using the sensor support.



1-retroreflector R is illuminated by the laser beam to measure **displacement** along the movement axis.
2-sensor 1 measure **horizontal straightness**
3-sensor 2 measure **vertical straightness**
4- reading of sensor 2 minus the reading of sensor 3 divided by 2 minus 3 distance = **Roll**

fig.6 Sensor support for measuring straightness, positioning and angles at the same time.

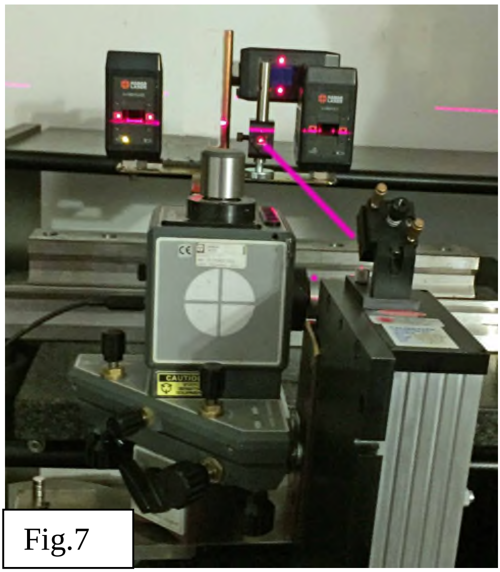


Fig.7

fig.7 Laboratory testing of simplified support for measurement of Hamarlaser L-743 scanning laser and Optodyne MCV 500 single beam interferometer.
This combination of 2 lasers and 4 targets have the capability of simultaneous measurement of 4 degree of freedom, nominally linear position, vertical straightness, horizontal straightness and roll angle. On the left the Hamarlaser and on the right on the same support the Optodyne interferometer. The sensor on the left and the sensor on the right are measuring vertical straightness, the difference between the two indication it is the Roll angle. The sensor in the center, that is rotated horizontally, is measuring horizontal straightness. The retroreflector in the center is measuring the movement in the longitudinal direction (distance displacement). the difference between the two indication it is the Roll angle.

3 Practical examples of results obtained with the volumetric compensation

Two are the practical examples for measurement and volumetric compensation that we recently performed of aerospace field that we want to show as example. The first is a machine of 6000x4000x1900 mm positioned in a climatic chamber where was obtained a final value of 57 micrometer with 4 diagonal of 6,5 m and an improvement in respect to the accuracy obtained with mechanical tuning only of 330%.

<table>
<tr><td>Measurement results</td><td>TIR</td><td>IMPROVEMENT</td></tr>
<tr><td>Without Compensation</td><td>0.190</td><td rowspan="2">330%</td></tr>
<tr><td>With VCS compensation</td><td>0.057</td></tr>
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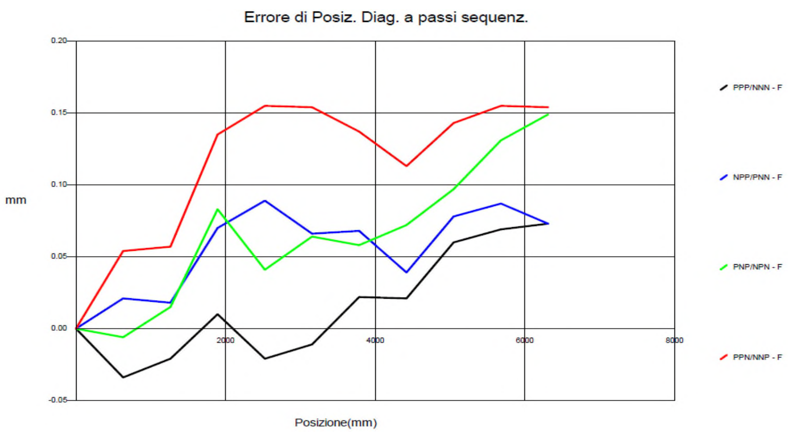
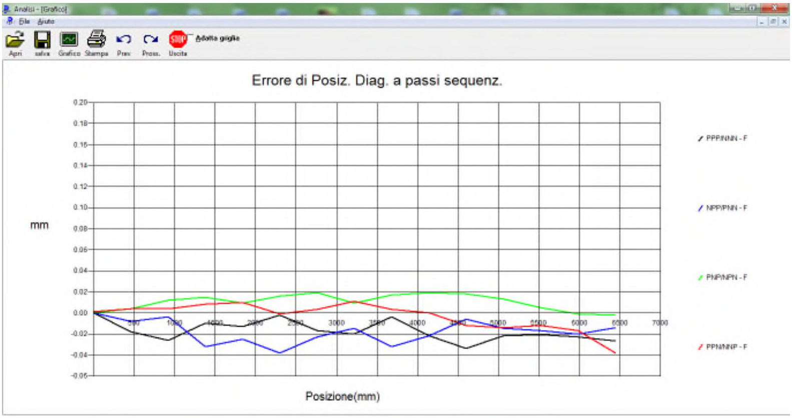
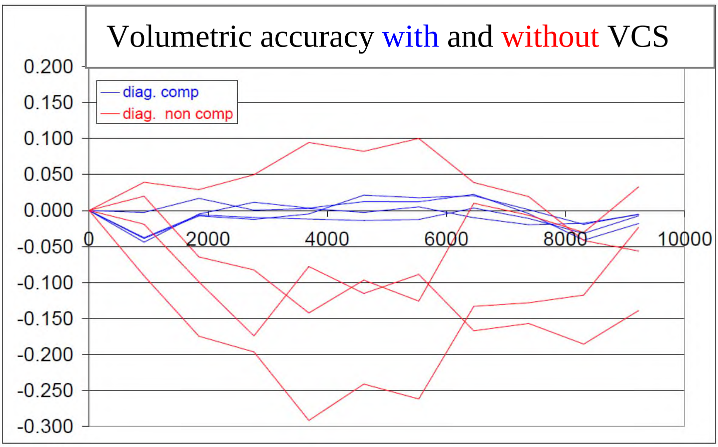




Lately a second similar machine but with lager dimensions was compensated on July 2018. The machine have the dimension of 7500x5000x2000mm with diagonals larger than 9m. The accuracy V(xyz) obtained is 0,066mm on the four diagonals on the volumes larger than 9m that is equivalent to 7,3 micrometer each meter .



4 Conclusion

In order to have a confrontation element for the evaluation of the reached results we do some consideration referring to the dimension variation on the machine structure produced by the temperature. The effect are different taking in consideration different materials, but starting from the statement of ISO-1 that specifies the standard temperature reference at 20°C for geometrical specification and verification, we can calculate the effect of the temperature variation from the basic 20 degree. We can take in consideration steel that have a linear thermal expansion of approximately 12 micrometer for each degree of temperature. Variation of one degree Celsius on 7 m produce a variation in length of 0,084 mm. The accuracy reached after the volumetric compensation is of the same order of magnitude of the influence of only 1 degree °C .

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