# COMPUTATIONAL ACCURACY ANALYSIS OF A COORDINATE MEASURING MACHINE UNDER STATIC LOAD

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## *Abstract*

This work presents a method of numeric simulation using finite element method (FEM) and geometrical analyses, to estimate the accuracy of a coordinate measuring machine (CMM) under static load, compared to its metrological behavior as a rigid body. A real CMM was CAD modeled and the deformation caused by a mass of 200 kg applied on its granite table was numerically analyzed by FEM. The deformed geometries of the machine guides were used in other computational analyses, now to estimate the measurement errors. The method is very practical to apply in any geometrical configuration of CMM, and useful of analyze the relation between the stiffness of the machine structure and its measurement uncertainty. Since it is not easy to calibrate a CMM with large masses on its table, a numerical simulation is valuable to estimate geometry deformations and avoid metrological problems.

**Keywords:** Coordinate Measuring Machine, Dimensional Metrology, Finite Element Method

## 1. INTRODUCTION

The operational and metrological performances of coordinate measuring machines have strongly improved in the last 10 years. Great technological evolution in all its components has improved the accuracy of the measurements and made the machines faster and more robust for industrial use. One of these evolutions was the implementation of software error correction, known as computer aided accuracy (CAA), taking the accuracy of the CMM beyond over its mechanical limitations.

With CAA, mechanical errors are compensated mathematically by the measurement software according to error values obtained during calibration tests. In these calibration tests, the machine measures standards like gauge blocks, step gages, ball bars, etc., or its movement is compared against a laser interferometer. In all these processes, the machines are evaluated under some common conditions: the machine is calibrated without load over its table and the speed and acceleration of the machine axes are very small.

These conditions are not usual during measuring processes in industry. Many machines are used to measure parts with tens or hundreds of kg, and the measurement speed of machines axes used in the dimensional control of mass production is usually very high. This difference between calibration and measurement processes can cause problems on the software error correction, due to the static and dynamic stiffness of the machine. Deformations of the machine structure change the geometry and position of guides and axes, and the CAA works as if the machine was a rigid body.

This work presents a numeric simulation using finite element method (FEM) and geometrical analyses to estimate the loss of accuracy of a coordinate measuring machine when operating under static load, compared to its metrological behavior as a rigid body. The mechanical structure of a real CMM was CAD modeled and numerically analyzed using FEM. In these analyzes, a static load of 200 kg was imposed to the table of the machine and a deformation analysis revealed the deformed geometry. This deformed geometry of the machine was used in another set of simulations, now to analyze the accuracy of the machine to some measurements. The results of these simulations can show differences between the accuracy of the machine when operating with and without loads. Since it is not easy to calibrate a CMM with large masses on its table, a numerical simulation is valuable to estimate geometry deformations and avoid metrological problems. The method has been developed to estimate also errors caused by dynamic loads but, at the time of this paper, only static loads were simulated.

## 2. COMPUTATIONAL ANALISYS OF A COORDINATE MEASURING MACHINE

To analyze the coordinate measuring machine under static load, the first step was to model its geometry on a CAD system. Based on a real CMM, the mechanical structure was CAD modeled. All parts, including table, guides and bearings were modeled based on real sizes of the machine and the assembly of individual parts was defined as realistic as possible.

Based on this CAD model, a deformation analysis was implemented using finite element software. A load of 200 kg was imposed to the machine table, at the center of measuring volume of the CMM. The restraints, as well as, the materials (steel, granite and ceramic) of the machine parts were defined according to the real conditions. Meshes were created on the machine structure and the new geometry was calculated, resulting in a deformed configuration of the machine (figure 1).

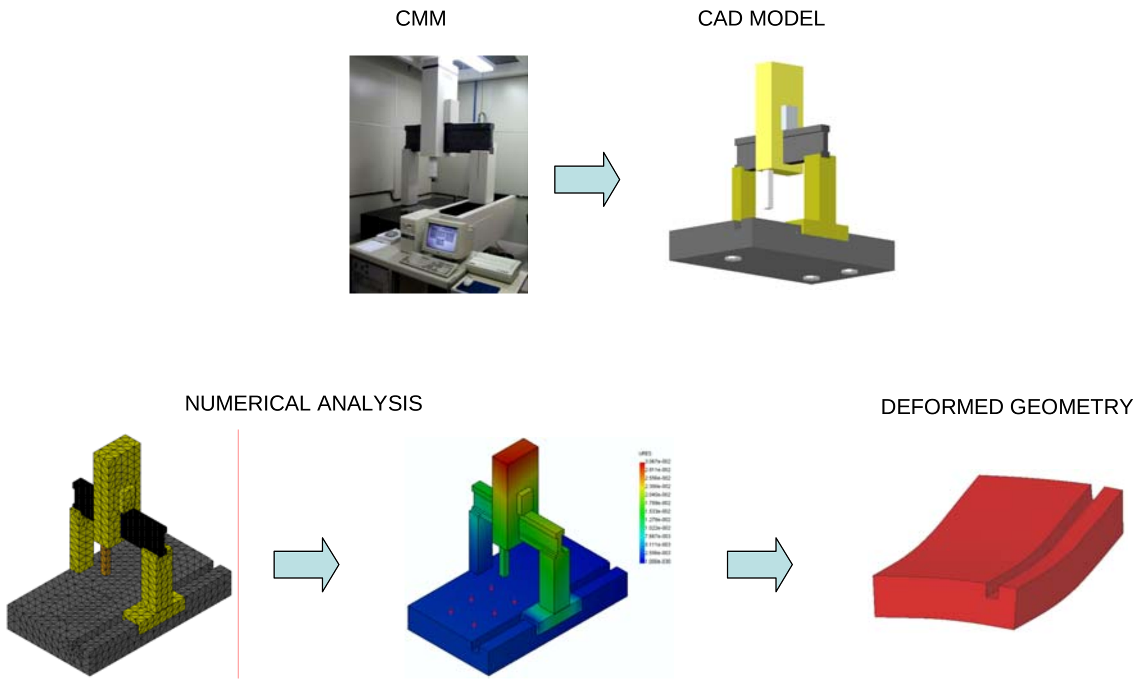


**Figure 1 – Deformation analysis: from real CMM to deformed geometry**

## 3. GEOMETRICAL SIMULATIONS OF MEASUREMENT ERRORS

The deformation analysis was performed with the machine bridge at several positions, in order to evaluate the path of the machine probe along the X axe (Figure 2). The position and displacements of some strategic points on the machine bridge and probe were monitored along X axe, in order to evaluate their path and angular errors.

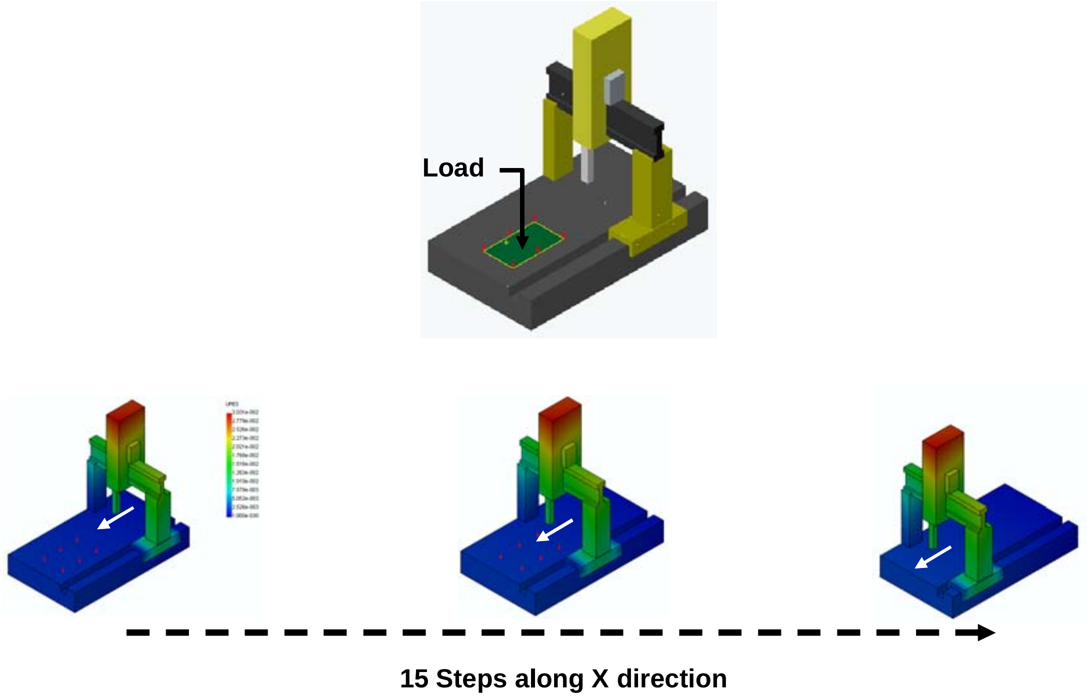


**Figure 2 – Path of the bridge over a deformed granite table**

These results were used in another set of numerical analysis, now to determine the geometric errors of straightness (vertical and horizontal), Roll, Pitch and Yaw of the machine bridge along its path (X axe) over the guides on the machine table. Figure 3 shows the errors of straightness in Y (XTY) and Z (XTZ), and figure 4 shows the angular errors of roll, pitch and yaw of the machine bridge.

For this machine, the results showed that the machine table has a good stiffness, assured by its strong mass of granite. As expected, the maximum error of straightness was in the vertical direction (XTZ), since the mass load causes a bending on the machine table and guides of the bridge.

The angular error of Pitch was the most critical, also because the bending of the table. But these errors became under acceptable values for this coordinate measuring machine. To some machines with structures of steel or aluminum, this influence could be more critical, and this analysis should be conducted to verify if the geometrical behavior is very affected by static loads.

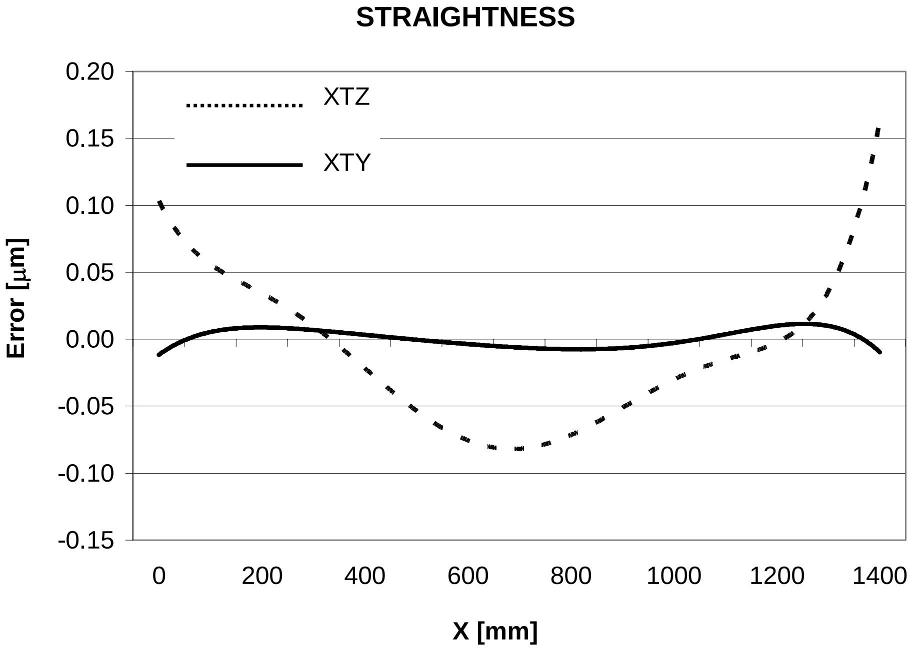


Figure 3 – Linear Errors of the machine bridge along its path

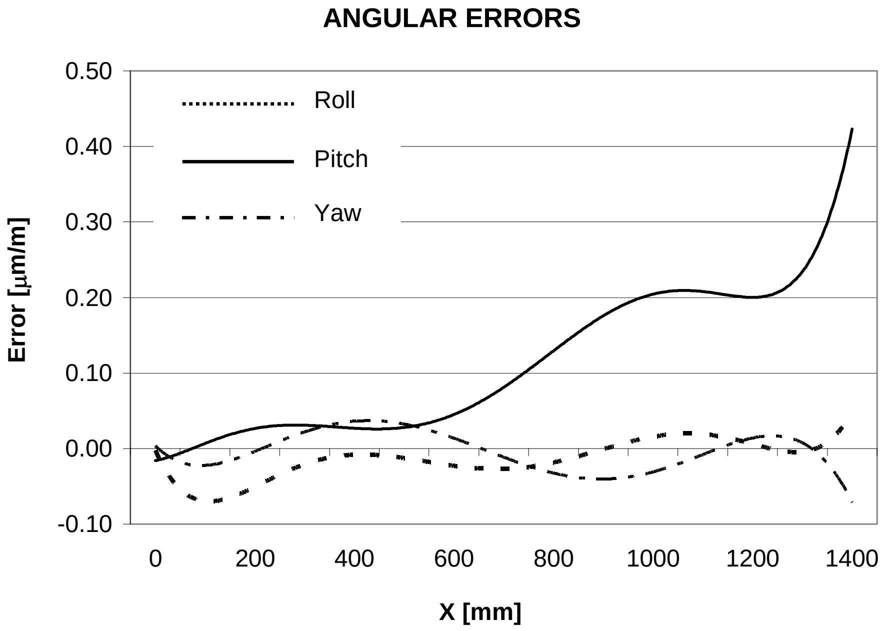
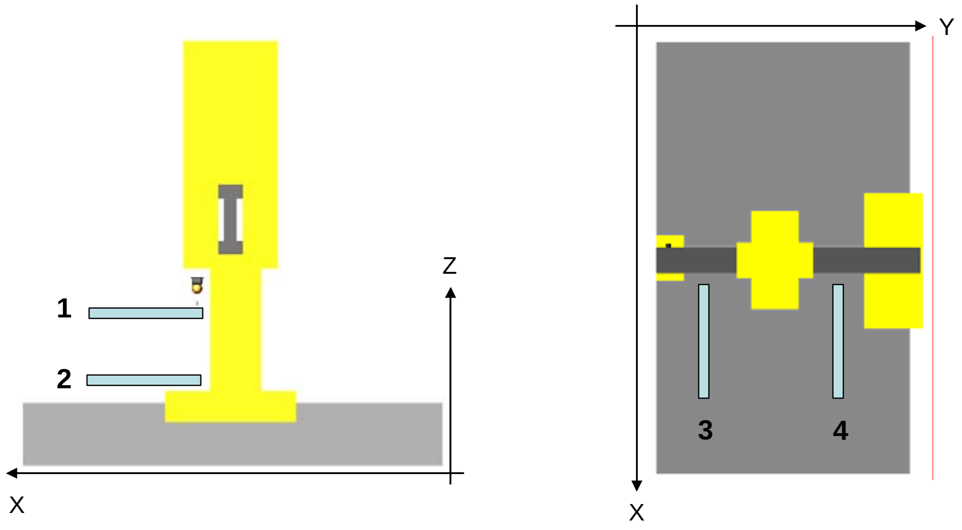


Figure 4 – Angular Errors of the machine bridge along its path

Using these geometrical errors, a geometrical simulation was performed to estimate the error that the machine would have to measure a length of 500 mm in some positions of the working volume. The measurements and results can be seen at figure 5. The errors of pitch and yaw were the main factors that influenced the results. It should be pointed out that this is the error caused only by the mass on the machine table and by the body forces of the machine itself.

From these results can be concluded that the stiffness of the machine table has a small influence over the results. Assuming that most part of the workpieces measured on this machine have less than 100 kg, it can be assumed that the static stiffness of the machine is suitable for its measurement task.

Applying the same strategy it is possible also to make several other simulations of errors for other measurement tasks (diameter, squareness, straightness, etc.). The position of the workpieces in the measuring volume must be indexed for the analysis.



| POSITION | Result |
|---|---|
| **1 (reference)** | 500.00000 mm |
| **2** | 500.00013 mm |

| POSITION | Result |
|---|---|
| **3 (reference)** | 500.00000 mm |
| **4** | 500.00004 mm |

**Figure 5 – Different measurement results at different positions**

More than analyze this machine, this paper has the objective to present a methodology to verify numerically the metrological behavior of coordinate measuring machines submitted to static loads of heavy workpieces.

## 4. CONCLUSIONS

This work presented the use of numerical methods to evaluate the metrological behavior of a coordinate measuring machine under static load. Applying simulation using finite element method (FEM) and geometrical analyses, it is estimated the accuracy of a coordinate measuring machine (CMM) under heavy static load, compared to its metrological behavior as a rigid body.

An evaluation was performed over a coordinate measuring machine with granite table. The machine was CAD modeled with the materials and restraints defined according to real conditions. A static load of 200 kg was applied on the machine table and the deformed geometry was used to estimate geometric deviations of the bridge along its path. Calculating deformed geometries for different positions of the machine probe along the working volume it is possible to estimate errors for different measurement tasks.

The simulation is practical of implementation and the results are very useful to estimate the metrological behavior of the CMM, mainly in situations where the workpieces have tens or hundreds of kg. The machine analyzed in this paper has a very strong mechanical structure, not more found in modern machines, which have been optimized to be lighter and faster.

The application of numerical analysis to evaluate geometric error of precision machine can be a powerful tool to verify the influence of some factor that affects its accuracy. Situations that would be difficult to verify experimentally can be estimated with good reliability. In this paper, a mass of 200 kg was loaded on the machine table. Other simulations of the machine behavior under dynamic loads and thermal loads have been tried and the results will be discussed on next papers.

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