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Assessment of Dynamic Errors of CMMs for Fast Probing

W. G. Weekers, P. H. J. Schellekens (2)
Eindhoven University of Technology, Precision Engineering Section, Eindhoven, Netherlands
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Abstract

Due to the demand for shorter cycle times of measurement tasks, fast probing at CMMs becomes more important and the influence of dynamic errors of CMMs will increase. This paper presents an assessment of dynamic errors due to carriage motion. Based on the analysis of the dynamic errors of a specific CMM a practical approach was chosen. In this approach the major joint deflections due to accelerations are measured with position sensors. Possibilities for estimating other joint deflections by analytical modelling of CMM components are discussed. Using a kinematic model of a CMM, the influences of the measured and estimated joint deflections on the probe position are calculated. A description of a measurement setup for one axis of a CMM is given to illustrate the approach. The results show that measurement and estimation for at least part of the dynamic errors is possible.

Keywords: CMMs, dynamic, error

1. Introduction

Coordinate Measuring Machines (CMMs) are nowadays widely used for a large range of measurement tasks. These tasks are expected to be carried out with ever increasing performance in terms of accuracy, speed and under worst environmental conditions (shop floor). As with machine tools, research effort is mainly spent on analysis, control and enhancement of the accuracy of CMMs. When considering the mechanical accuracy of multi-axis machines such as CMMs three main sources of quasi-static errors can be distinguished (see e.g. [9, 10]):

- Geometric errors due to the limited accuracy of the components, like guideways and measurement systems. These errors depend on the manufacturing accuracy of these components and the adjustment accuracy during installation or maintenance.
- Errors related to the finite stiffness of the components of a CMM, mainly caused by the weight of moving parts. These errors depend on the stiffness and weight of the components and their configuration.
- Thermal errors like expansion and bending of guideways due to uniform temperature changes as well as temperature gradients. These errors depend on the machine structure, material properties and the temperature distribution of the CMM, influenced by external sources such as the environmental temperature and by internal heat sources such as the drives.

Most of the research concerning CMM accuracy has been focused on these quasi-static errors. But besides these quasi-static errors CMMs are also influenced by dynamic errors, like acceleration dependent deformation of CMM components due to part movements and vibrations, both self-induced and forced. These dynamic errors depend on the CMMs structural properties, like mass distribution, component stiffness and damping characteristics, as well as on control- and disturbing forces.

For high measurement accuracy the effects of mentioned error sources on the CMM accuracy have to be small. So in general a lot of effort is spent to eliminate these error sources or to keep them small, which yields in principal the following conditions for CMM design and operating conditions:

- high manufacturing and adjusting accuracy;
- high component stiffness and low mass;
- temperature conditioned environment and small internal heat sources;
- vibration isolation and smooth movements during probing.

However some of these conditions are difficult to combine, like high stiffness and low mass or they are conflicting with the wish for higher operating speed and shop floor conditions. An alternative for these design and operating conditions is to obtain sufficient knowledge of all the errors and to apply software error compensation for these errors. This method has been applied successfully by several researchers for geometric (e.g. [1, 5, 10, 11, 14]), thermal ([10]) and finite stiffness errors ([9]).

Until now little attention has been paid to dynamic errors of CMMs and possibilities for compensation. Research concerning dynamic behaviour of CMMs has been focused on theoretical and experimental methods for identifying the vibration modes of CMMs in order to improve CMM design (e.g. [6, 8]).

In general dynamic errors are regarded as random and not systematic. Therefore these errors are considered not to be suitable for software error compensation.
Figure 1: CMM investigated at the TUE.

As a result of this, measurement speed is often kept very low (see also [7]) to avoid these dynamic errors, and cycle times of measurement tasks are long. However, with the demand for the increase of probing speed, the analysis of dynamic errors is becoming an increasingly important issue in CMM research.

Also at the Precision Engineering section of the Eindhoven University of Technology (TUE) CMM research is now concentrated on fast probing and dynamic errors. First contributions to this subject were focused on the identification of vibration modes ([6]) and the estimation of the vibration amplitudes ([12]). At the moment a research project is carried out aimed at the identification and description of dynamic errors during fast probing of an existing CMM (figure 1).

The goal of this research is to investigate the possibilities for software error compensation of dynamic errors of CMMs and the practical implementation of a compensation method. This paper presents an assessment of dynamic errors induced by CMM movements, based on measurement of joint deflections.

3. Modelling

Similar to the way the quasi-static errors are dealt with, assessment of the dynamic errors consists of two parts: identification of the individual dynamic errors and prediction of their effects on the probe position, using a kinematic model. The kinematic model of a CMM defines the spatial relationship between the machine components and the probe position, and can be based on homogeneous coordinate transformations or on a more simple vector model.

Since this research is aimed at CMMs, which are in general multi-axis machines with three perpendicular prismatic axes, the vector model is suitable. However if a more general model is necessary the kinematic model based on homogeneous transformations is preferable (e.g. [10], [13]). The kinematic model has a discrete number of degrees of freedom located at the prismatic joints (figure 1). All the dynamic errors are considered to be located at the joints, including bending of beam shaped components. For the dynamic errors due to the finite stiffness of air bearings this will coincide with the physical reality. For deformations of beam elements like guideways, a method for combining the errors to the joint positions has to be developed. So in general a certain dynamic joint error consists of the contributions of several components, like air bearings, carriages and guideways. However, for the CMM investigated at the TUE bending turned out to be very small compared to e.g. air bearing compliance. Superposition is used to yield the total joint error, related to a certain degree of freedom.

3.1. Kinematic model

The kinematic model relates the dynamic errors of a CMMs components to the errors at the probe position. Because it is assumed that all dynamic errors are located at the machine joints, the model has to describe the relations between the errors related to the degrees of freedom of each joint and the probe position. For example, the CMM of figure 1 has three carriages each with six degrees of freedom, three rotations and three translations. The dynamic rotation and translation error vectors of the i-axis can be defined as:

\[ B_i = [R_{xi}, R_{yi}, R_{zi}]^T, I_i = [T_{xi}, T_{yi}, T_{zi}]^T \]  (1)

The error \( dP_i(P) \) at the probe position \( P \) due to dynamic rotation errors can be found using the position vector of the carriage and calculating the vector product:

\[ dP_i(P) = B_i \times P_{io}, \quad P_{io} = [x_{io}, y_{io}, z_{io}]^T \]  (2)
The position vector $\mathbf{P}_i$ describes the position of the probe relative to the scale of axis i (figure 2). The total error $\mathbf{d}(x, y, z)$ for the i-carriage can be found by adding the dynamic translation error vector:

$$\mathbf{d}(x, y, z) = \mathbf{d}(\mathbf{P}_i) + \mathbf{P}_i = \mathbf{d}(\mathbf{P}_0) + \mathbf{P}_i$$

The total error $\mathbf{d}(x, y, z)$ at the probe position consists of the contributions of all three guideways. For the three carriages x, y and z this yields:

$$\mathbf{d} = \mathbf{d}_x + \mathbf{d}_y + \mathbf{d}_z$$

### 3.2 Dynamic joint errors

The main idea of this assessment of dynamic errors is that they are considered all to be concentrated in the joints, including bending of beam components as will be explained later, and that they can be either measured using sensors or calculated with a model describing the relations between the non-measured and measured errors of one particular joint. These relations in general are influenced by the vibration modes of the CMM. Here it is assumed that only the quasi-static deflections of the components and the lowest vibration modes contribute significantly to the dynamic error of a particular joint. The most important components of a CMM are considered as flexible elements, undergoing deflections and vibrations due to carriage movements. These deflections and vibrations result in rotation and translation errors of the components.

To illustrate this idea a model for the prismatic y-joint of the CMM depicted in figure 1 is given (figure 3). The y-axis consists of a guideway, air bearings and a carriage. The dynamic errors of the y-joint are influenced by the connected x-traverse. In general all these components have finite stiffness. So in case of y-axis movement all these components will experience deflections due to acceleration forces, resulting in rotation and translation errors at the y-joint. For example rotations $R_{yz}$ shown in figure 3, but also rotations $R_{xy}$. The y-axis movement will also affect the components of other axes. The x-axis components for example will experience rotations $R_{xz}$ and the z-axis components rotations $R_{zx}$. The total y-joint error can be found by superposition of the component errors. For the error $R_{zy}$ this can be written as:

$$R_{zy} = R_{zy, gui} + R_{zy, air} + R_{zy, car} + R_{zy, x-tra}$$

In a similar way expressions for all other joint errors can be found. In principle all these error components have to be known at the moment of probing. With respect to the identification of these errors the following aspects have to be considered:

- Many of the errors will have no significant contribution due to a specific axis movement. Especially the translation errors are small compared to the effect of the rotation errors.
- The significant errors can be identified most accurately by direct measurements using sensors mounted at the CMM.
- An alternative for measuring an error is combining it with another measured error by describing the relation between these errors.

Of course the number of sensors used should be as small as possible. Therefore as many errors as possible have to be combined. Only errors with no significant phase differences can be combined easily. Combination of the errors is machine dependent.

Taking the situation of figure 3 as an example we can illustrate the method. The components belonging to the y-joint are considered as masses connected by springs. In general the relation between a series of mass-spring elements is described by sets of differential equations. If the masses (or moments of inertia) between the springs are small compared to the mass connected to the last spring of the joint, the dynamic forces on these elements may be neglected. In this case all spring elements experience the same force (or moment) and an algebraic expression between the errors, depending on the stiffness ratios, can be found. In this way nonmeasured errors of parts with relative low mass, close to the joints can be combined easily with the measured errors.

The usefulness of this method is of course dependent on the CMM used, more particular it's components, which errors can be measured and the assumptions which can be made regarding the dynamic behaviour. It will be shown that the method can be used in the case of the CMMs of the type investigated at the TUE.

### 3.3 Dynamic joint errors of a specific CMM

The CMM used for our experiments (TUE-CMM) is depicted in figure 1. The dynamic behaviour of this CMM is largely defined by the movements of the traverse carrying the x- and z-axes and which is connected to the y-carriage.
A series of measurements, based on angular laser interferometry, were made to identify the dynamic behaviour and the weak elements of the TUE-CMM ([4]). These measurements show that the guideways are relatively stiff. The weak elements are the drive system, the air bearings, the carriages holding these bearings, the support of the y-guideway and the connections between the carriages and guideways. The main contribution to the dynamic error at the probe position is accounted for by the rotation of the x-traverse around the z-axis at the y-carriage position. The low stiffness of the y-drive also results in large movements, but since these are translations, they are accounted for by the scale readings and don't result in measurement errors. When the y-axis is moved at higher speeds (70 mm/sec) deflections are measured at the probe position during starting and stopping (figure 4). Movement of the y-carriage induces vibrations mainly due to the low stiffness of the y-drive, which also causes the rotation vibration shown (= 5 Hz).

An important part of the identification of the dynamic errors is the measurement of the most important errors. At the CMM inductive displacement sensors can be used to measure the relative movement of the carriages with respect to the guideways. Figure 5 gives an overview of all possible sensor locations for the TUE-CMM. In principle 13 joint errors can be measured, but in order to test the usefulness of the method only two sensors are used for the moment. With these mounted symmetrically at the y-carriage the rotation R_{zy} of the carriage around the z-axis, relative to the y-guideway can be measured (see figure 5).

The rotation R_{zy} can be calculated from the measured displacements dS_1, dS_2 and the distance l_y:

\[ R_{zy} = (dS_1 - dS_2) / l_y \]  

In this way the dynamic errors due to the finite stiffness of the air bearings can be identified. Measurements at the y-carriage show that besides the air bearings also the carriage itself and the guideway (including the support) contribute to the dynamic error, due to their finite stiffness.

In order to estimate these contributions, the following assumptions are made regarding the dynamic behaviour of the y-carriage:

- The damping doesn't cause any significant phase shift between the elements. This assumption has to be verified by suitable measurements.
- The stiffness of the elements is not frequency dependent so the static stiffness of the elements can be used, especially for the low frequencies considered.
- The moments of inertia of the carriage and the support are negligible compared to the large combined moment of inertia of the traverse, x- and z-axis.

In this case the moments on the guideway, air bearings and carriage are equal:

\[ M_{z,gui} = M_{z,air} = M_{z,car} \]  

Using the static stiffness k_i of each component this yields:

\[ R_{zy,gui} k_{gui} = R_{zy,air} k_{air} = R_{zy,car} k_{car} \]  

So the total error can be written as:

\[ R_{zy,tot} = [1 + k_{air} k_{gui} / k_{car}] R_{zy,meas} \]  

with: \[ R_{zy,meas} = R_{zy,air} \]

In this way a (static) stiffness ratio can be defined:

\[ f_{R_{zy}} = 1 + k_{air} k_{gui} / k_{car} \]  

This ratio will be used to calculate the total joint error from the errors measured by the displacement sensors.

The guideways are also assumed to have finite stiffness in general. These guideways can be considered as beam elements. In principle the errors due to beam deflections can be calculated from the load estimated from the joint errors at the carriage located lower in the kinematic chain of the CMM.
However extra assumptions have to be made with regard to the load distribution on the beam due to the accelerations. Because the beams are in fact continuous elements the rotation and translation errors due to beam deflections depend on the position along the beam. Using the relations describing these beam deflections, matching rotation and translation errors at the joints have to be found which can replace the beam errors but which will have the same effects on the probe error. In this way beam deflections are expressed in terms of joint deviations to fit the model with the discrete number of degrees of freedom. Since the guideways of the TUE-CMM have relatively high stiffness compared to the joint elements, dynamic beam errors will not be considered further here.

4. Measurements

In order to verify the above presented method, measurements were performed at the TUE-CMM, using the measurement setup with the two position sensors mounted at the y-carriage (see figure 5) to measure the carriage rotations $R_{zy}$ (3]). A digital amplifier and PC were used to record the signals from these sensors. The sensors were calibrated for translations perpendicular to the guides using a laser interferometer. From the sensor readings the rotations are calculated. The several dynamic errors and the total joint error were measured using a angular interferometer suitable for dynamic measurements. For each measurement the angular retroreflector was attached to the components to be measured and the interferometer to the granite table of the CMM. The rotations of the elements contributing to the joint error $R_{zy}$ were measured under static load. From these static measurements the ratio $f_{R_{zy}}$ was found using (10):

$$f_{R_{zy}} = 1 + 0.4 + 0.7 = 2.1 \quad (11)$$

This ratio can be used to calculate the total dynamic joint error $R_{zy}$ from the measured rotations. Dynamic measurements of the rotation at the upper part of the y-carriage are used to verify this. Figure 6 shows an angular laser measurement of the rotation $R_{zy}$ and a sensor measurement of the same rotation multiplied with the static ratio. From the graphs it can be seen that the calculated static ratio yields good results when used to characterise identify this dynamic error.

Laser measurements were also performed with the angular retroreflector of the laser interferometer at different positions along the x-guideway, taking sensor measurements at the y-carriage. As shown in figure 7 the ratio between the measurements is again reasonably constant indicating no significant bending of the x-guideway. The ratio itself is somewhat higher than for the measurements at the y-carriage, so an extra rotation is introduced at the connection between the x-guide and the y-carriage. This rotation can also be accounted for by the ratio making up the total dynamic joint error.

Here only one joint error is measured. In order to predict the total dynamic error at the probe position accurately, more errors have to be measured by implementing more sensors at different positions. The measurement setup is also being improved for better measurement of possible phase shift between the elements.

It should be pointed out here that from the measured rotations and known stiffness of the components, in principle, forces and accelerations can be estimated. These can be used to estimate other errors and their effects on the probe position. For example the $R_{yx}$ and $R_{xz}$ rotation errors due to movement in y-direction can be estimated from the measured $R_{zy}$ error at the y-carriage. In this way less sensors are necessary. Since the translation error $T_{xy}$ measured by the y-carriage sensors are relatively small, it is also worthwhile to consider the possibility of measuring the rotation $R_{zy}$ with only one sensor. These items are subjects for future research.

For the present measurement setup inductive position sensors were chosen for reasons of availability and experience. But in principle also other sensor types, such as capacitive or pneumatic sensors, might be suitable for these measurements.
5. Conclusions

In this paper the identification and description of dynamic errors of CMMs during fast probing are discussed. With the demand for higher measurement speeds these dynamic errors are becoming increasingly important compared to other errors. Since accurate analytical modelling of dynamic errors is very difficult, a combined practical and theoretical approach for the assessment of dynamic errors of CMMs for fast probing is chosen. The given approach is based on the direct measurement of the most important dynamic joint errors due to the accelerations during movement, modelling of other dynamic errors and calculation of the effects of these errors on the probe position.

For modelling convenience all dynamic errors are considered to be located in the joints of the CMM. It is shown for a particular CMM that good results can be obtained by measuring part of a dynamic joint error and calculating the total joint error, using a static stiffness ratio.

More research has to be done in order to investigate the influence of the damping and to establish relationships between other joint errors and axes. Furthermore the usefulness of the proposed method for other CMMs has to be tested.

Other interesting research topics with respect to the identification of dynamic errors is the use of different sensor types and the possibilities of using only a small number of sensors to identify more dynamic joint errors. In the latter case more relations between the errors have to be established.

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Literature