Fixture evaluation based on CMM

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Abstract

Fixture evaluation is an important part of a fixture design and manufacture, because it provides quantitative information of fixturing errors. Such information is useful for the validation of theoretical analysis and the evaluation of the fixture performance. It also provides suggestion of fixture improvement. The evaluation of fixture performance includes checking workpiece loading repeatability, workpiece distortion, and examining the workpiece movement caused by clamping and machining force. A coordinate measurement machine (CMM) measurement method for fixture evaluation was developed based on the transformation of coordinate systems (CS) and the measurement of datum displacements. A turbine blade fixture was assessed as an example.

1 Introduction

Fixtures are used to locate and to hold one or several workpieces for machining. Location and orientation of a workpiece depends on fixture performance, which is strongly influenced by the characteristics of workpieces (geometry, materials and tolerance) and the design of fixture elements (spatial layout and clamp mechanism). A good fixture should possess the ability of correctly locating workpiece and preventing workpiece from slippage. Meanwhile it should also be able to ensure minimum workpiece distortion, sufficient clamping force, high efficiency, good stability, and a low cost.

A fixture design and manufacture process includes four stages: fixture design, fixture manufacture, machining test and fixture evaluation. If the performance of a fixture is unsatisfied, a modification of the fixture has to be carried out. Most fixture research to date has been devoted to the fixture design stage for: a) workpiece location [1]; b) workpiece distortion [2][3]; c) workpiece movement
during machining [4][5]; d) errors of geometry and tolerance [6][7]; e) and stability of fixturing [8]. Some researchers considered the combination of location, distortion and movement etc. [9][10]. However the majority of work has been focused on the theoretical analysis of fixture performance. The analysed results were often verified by using workpieces of simple block-shapes. As a result, the performance of a fixture for those workpieces with complex geometry did not always follow the theory prediction.

In practice, a lot of fixture problems remained unknown until the fixture has been manufactured and the workpiece machined. As a consequence, the fixture structure might need to be redesigned. These problems are relevant to fixture evaluation. This paper presents a systematic fixture evaluation method to analyse the location, movement and distortion of a workpiece in a fixture. The result may be applied to analyse fixturing error sources, to evaluate fixture performance, to verify theory prediction and to assess the fixture improvement.

Because of its high accuracy and easy manipulation, a coordinate measurement machine (CMM) is a commonly used measurement facility in a metrology workshop. Thanks to the programmable features of a CMM, it is convenient to use them for indirect measurement, such as coordinate system (CS) transformation for a fixture. Therefore, the CMM may be considered as the most convenient measurement device for fixture evaluation.

2 CMM-based fixturing evaluation and analysis

Fixture evaluation is normally carried out after a fixture is designed, manufactured and assembled, and after a workpiece is machined. A fixturing error is the workpiece position error relative to the fixture datum generated during clamping and machining. Normally it is a result of inadequate location and clamping. The comparison of fixturing errors and allowable tolerance would provide useful information to judge whether or not a fixture should be acceptable and how much improvement had been made to the fixture.

For the purpose of fixturing evaluation, a CMM program should cover: (a) fixture clamp evaluation, which would test workpiece location repeatability and distortion under clamping forces; (b) fixture machining evaluation, which would measures workpiece movement and workpiece distortion caused by the machining forces.

A test of location repeatability is required to verify whether the locators of a fixture can constrain six degrees of freedom (DOF) of a workpiece and whether the clamping device of the fixture is capable of securing the workpiece in the right orientation and location. The test method is to load a workpiece on a fixture several times and to measure the datum displacement against the first measured CS. Such repeatability tests will show the poor constraint directions. Poor location repeatability means that the degrees of freedom of the workpiece are not all constrained sufficiently by the locators. The locator position and the clamping mechanism have to be modified if the repeatability is poor.

Workpiece distortion herein comes from clamping and machining. Ideally the clamping force should be large enough to stop a workpiece from moving in a
fixture during machining, and at the same time it should be small enough not to distort and damage the workpiece. Distortion of a workpiece is the change of relative positions of different parts of the workpiece. The distortion measurement is to measure relative displacement between different parts of the workpiece before and after clamping. The measured distortion value can be utilised to verify theoretically predicted distortion given by finite element analysis or by other computer calculation. Fixture distortion caused by machining force also needs to be measured and evaluated in the same way.

Machining forces have to be balanced by clamping forces and reaction forces from locators, otherwise the workpiece will move away from its original position. Assume the fixture is correctly positioned on the machine during machining, the workpiece movement can be measured using the fixture as reference. If there is no distortion on the un-machined side of the workpiece, the datum displacement of the un-machined side of workpiece can be treated as the workpiece movement against the fixture. When large movement is encountered during machining, the measurement data will tell the inadequate constraint directions. Rearrangement of the fixture layout may be required.

3 CMM measurement strategy

3.1 Coordinate system transformation

Coordinate System (CS) transformation, including CS translation and CS rotation, play a vital part in the CMM measurement. A coordinate system on point i can be written as $CS_i = [X_i, Y_i, Z_i]$, where $X_i, Y_i, Z_i$ are vectors of the X-axis, Y-axis and Z-axis respectively. Assume there are two CSs existing in the space: $CS_1 = [X_1, Y_1, Z_1]$, and $CS_2 = [X_2, Y_2, Z_2]$ as shown in Figure 1, the transformation from $CS_1$ to $CS_2$ is written as:

$$Tr(CS_1, CS_2) = [X, Y, Z, \gamma, \beta, \alpha]$$

(1)

Where $X, Y$ and $Z$ are parameters indicating the CS translation; $\gamma, \beta$ and $\alpha$ are parameters presenting the Z rotation, Y rotation and X rotation respectively. To translate $CS_1$ to $CS_2$ is to simply move $CS_1$ origin to $CS_2$ origin without changing the axes directions. The translation values $X, Y$ and $Z$ are the coordinate values of the $CS_2$ origin relative to the $CS_1$. After the translation, the $CS_1$ is moved to the $CS_1'$, where the origin of the $CS_1'$ coincides with that of $CS_2$.

The $CS_1'[X_1', Y_1', Z_1']$ can be further aligned with $CS_2'[X_2', Y_2', Z_2']$ by rotating its axes. As shown in Figure 2(a), the coordinate system $CS_1'[X_1', Y_1', Z_1']$ is the translated $CS_1$ in Figure 1. To align $X_1'$ to $X_2'$, the $X_1'$ should firstly rotate an angle $\gamma$ to $X_3'$, which is the projection of $X_2'$ on the $X_1'Y_1'$ plane of $CS_1'$. Then the $X_3'$ can be aligned to $X_2'$ by rotating an angle $\beta$. The vector $X_1'$ of $CS_1'$ will be aligned with the vector $X_2'$ of $CS_2$ after these two
rotations. As shown in Figure 2(b) $\alpha$ is the rotation angle from $Y1'$ to $Y2$. The vector $Z1'$ of CS1' will be aligned with the vector $Z2$ of CS2 automatically after $X1'$ is aligned with $X2$ and $Y1'$ is aligned with $Y2$. The CS transformation is actually to determine the values of $X, Y, Z, \gamma, \beta, \alpha$. If the relative position between CS1 and CS2 is unchanged, when the CS1 is moved to a new position CS1'', then new position of CS2 can be written as:

$$CS2'' = CS1'' + Tr(CS1, CS2)$$

(2)

Figure 1: CS translation from CS1 to CS2

Figure 2: Rotation from CS1' to CS2

3.2 Fixturing errors measurement

As mentioned before, the fixturing errors evaluation is composed of the evaluation of location repeatability, workpiece distortion and workpiece movement. To fulfill such operations, four coordinate systems are required. The labels of these CSs are shown in Table1. It should be noticed that all CSs measured by the CMM are based on the absolute CS in the CMM space. A CS transformation is inevitable when the fixture or the workpiece is to be used as references for the fixturing error measurement.
A procedure of fixturing error measurement is listed as below.
1. Locating and clamping a workpiece onto the fixture;
2. Measuring the positions of CS$_{b1}$, CS$_{b2}$, CS$_b$, and CS$_f$, and calculating relative positions between these coordinate system frames.
3. Machining of the workpiece.
4. Measuring new positions of the CS$_{b1}$, CS$_{b2}$, CS$_b$, and CS$_f$, and calculating position changes caused by the machining.

In this measuring procedure, the fixture together with the clamped workpiece has to be taken off the CMM once step 2 has finished. After step 3, the machined workpiece together with the fixture should be put back on the CMM table in order to carry out further measurement. Two situations will arise.

Case 1: the fixture can be kept at the same position on the CMM table before and after machining by using a special device.

Case 2: the fixture position on the CMM table is changed before and after machining.

Although an expensive special device is required for Case 1, it gives higher measurement accuracy and less measurement time. Case 2 is a more flexible and cheaper option.

The measurement method for the location repeatability and fixturing errors caused by the clamping force are the same as that for fixturing error caused by the machining. Therefore only method for measuring fixturing errors caused by machining is discussed below.

In Figure 3, a measured CS before machining is labelled with (*) and a measured CS after machining is labelled with (+). For example, the CS on the machined side of workpiece before machining will be presented as CS$_{b2}$ (*)

With the assumption that no distortion occurs on the un-machined side of the workpiece, the datum displacement on the un-machined side of the workpiece relative to the fixture is regarded as the workpiece movement. Since the fixture position can be kept unchanged during machining and measuring procedure, both the CMM absolute CS and the fixture CS can be used as the measuring reference. Thus the movement of the workpiece is:

$$Mov = Tr (CS_{b1}(\cdot), CS_{b1}(\cdot))$$  \hspace{1cm} (3)

Before clamping or machining, the relative position $Rel$ between CS$_{b1}$ (*) and CS$_{b2}$ (*) is

$$Rel = Tr (CS_{b1}(\cdot), CS_{b2}(\cdot))$$  \hspace{1cm} (4)

If there is no distortion caused by machining, the CS on the machined side of workpiece, named CS$_{b2}$ (*), will be

$$CS_{b2}(\cdot*) = CS_{b1}(\cdot) + Rel$$  \hspace{1cm} (5)

The difference between CS$_{b2}$ (* *) and CS$_{b2}$ (+) will be the distortion $Dist$.

$$Dist = Tr (CS_{b2}(\cdot*), CS_{b2}(\cdot))$$  \hspace{1cm} (6)
In this case, the fixture CS position after machining will be different from that before machining. Relative position between the fixture CS and the CMM absolute CS will be changed. The fixture CS can still be used as the reference for both distortion and movement measurements, but the relative position between the fixture and the workpiece need to be calculated and recorded.

The relative position between \( CS_f \) and \( CS_{bl} \) before machining is:

\[
Rel1 = Tr(CS_f^{(*)}, CS_{bl}^{(*)})
\]  

The relative position between \( CS_{bl} \) and \( CS_{b2} \) before machining is

\[
Rel2 = Tr(CS_{bl}^{(*)}, CS_{b2}^{(*)})
\]  

Assume there is no movement caused by machining on the un-machined side of the workpiece, \( CS_{bl} \) will not move with respect to the fixture itself. In this case, \( CS_{bl}^{*(-)} \) is defined as the \( CS_{bl} \) position relative to the absolute CMM reference after the fixture is put back on the CMM.

\[
CS_{bl}^{*(-)} = CS_f^{(*)} + Rel1
\]  

If \( CS_{bl}^{(*)} \) is the actual measured \( CS_{bl} \) position, then the workpiece movement \( Mov \) is the position difference from \( CS_{bl}^{(*)} \) to \( CS_{bl}^{(-)} \)

\[
Mov = Tr(CS_{bl}^{*(-)}, CS_{bl}^{(*)})
\]  

Assume there is no distortion generated during machining, the position of \( CS_{b2} \) relative to the CMM absolute reference will be \( CS_{b2}^{*(-)} \).

\[
CS_{b2}^{*(-)} = CS_{b1}^{(*)} + Rel2
\]  

Then the distortion of the workpiece will be:

\[
Dist = Tr(CS_{b2}^{*(-)}, CS_{b2}^{(*)})
\]  

3.3 Average CS and CS iteration

In order to reduce the uncertainty in the case 2, an average CS may be employed:
This is because the standard deviation ($\sigma'$) of the sample average is smaller than that ($\sigma$) of single measurement.

$$\sigma' = \frac{\sigma}{\sqrt{n}}$$  \hspace{2cm} (14)

Apart from the average CS program, an iteration program was employed to minimise the measurement error caused by surface roughness. Because the CMM program ran automatically without human interference, the coordinates of a point in the program remained the same without update. As shown in Figure 4(a), if the fixture position changes and the fixture CS and workpiece CS were not updated, the point coordinates relative to the old CSs would point to somewhere else during a new measurement. As shown in Figure 4(b), the methodological error due to the unevenness of a surface was inevitable if the stylus pointed to different position of a surface. In fact, the non-orthogonal and curved features of datum surfaces would make the situation worse. To minimise this type of error, the iteration program was used to find a CS, which might give a better estimate of the actual position of the workpiece or the fixture. The flow chart of the iteration program is illustrated in Figure 5.

![Figure 4](image-url)  \hspace{2cm} ![Figure 5](image-url)

**Figure 4:** The deviation cause by surface unevenness  

**Figure 5:** Flow chart of the iteration program
4 Machined surface error

A machined surface error is the difference between the theoretical machined surface and the actual machined surface. Figure 6(a) shows a workpiece, where $S$ is the surface to be machined. In Figure 6(b), the workpiece should ideally be located at the position aligned with the CS1, which is a coordinate system assigned to the workpiece before machining. However, if the location of the workpiece during machining is changed to the position indicated by the CS2, $S$ in CS1 named $S_{cs1}$, will be moved to $S$ in CS2, named $S_{cs2}$, thus a machined surface error will be created as shown in Figure 6(b). In fact, $S_{cs1}$ is the actual machined surface of $S$ where $S_{cs1}$ is theoretical machined surface. The difference between $S_{cs1}$ and $S_{cs2}$ is the machine surface error caused by the workpiece displacement. Suppose the point $P1(x1,y1,z1)$ relative to CS1, named $P1(x1,y1,z1)_{CS1}$, is a point of $S_{cs1}$. When the workpiece moves to the position of the CS2, the point $P1(x1,y1,z1)_{CS1}$ should move to point $P2(x1,y1,z1)_{CS2}$, which is the corresponding point of $P1$ in CS2. The distance between the $P1$ and $P2$ is a machining error. Coordinate values of point $P2$ in CS1 will be $P2(x2,y2,z2)_{CS1}$, which can be calculated by the CS transformation from CS1 to CS2. Assume the CS transformation from CS1 to CS2 is:

$$Tr(CS1,CS2) = [u,v,w,y,a]$$

where $u$, $v$ and $w$ are the translation components, and $a$, $b$ and $c$ are the rotational components, then the coordinate values of point $P2$ in CS1 is

$$P2(x2,y2,z2)_{CS1} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \alpha & \sin \alpha \\ 0 & -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \cos \beta & 0 & -\sin \beta \\ 0 & 1 & 0 \\ \sin \beta & 0 & \cos \beta \end{pmatrix} \begin{pmatrix} x1+u \\ y1+v \\ z1+w \end{pmatrix}$$

(15)

Figure 6: Machined surface error

5 Example

A blade fixture as shown in Figure 7 was evaluated by the described CMM method. A feature on the root side of a blade was machined and the measurement results were presented in Table 2. The measurement results showed that the
distortion of the fixture was so small (close to the range of the CMM accuracy) that it could be ignored. It can be seen that the repeatability of workpiece location is far better than the workpiece movement. For the machining performance, poor movement constraints were found in X, Y translation and Z rotation as shown in table 2. The re-examination of the constraints for the DOF was required.

![Figure 7: A fixture containing a blade](image)

**Table 2 measurement results of a fixture assessment**

<table>
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<th>Clamping performance</th>
<th>Machining performance</th>
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<tbody>
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<td>Blade Repeatability</td>
<td>Clamping Distortion</td>
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<td>Y shift</td>
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6 Conclusion

Fixture evaluation should be carried out after a fixture has been designed, manufactured and assembled, and after a workpiece has been machined. The evaluation involves the assessment of the fixture performance during clamping and machining. The method presented in the paper can be used to verify the results of theoretical fixture analysis and redefine fixturing parameters. This method is a multi-objective evaluation, which checks:

1) Workpiece repeatability of loading;
2) Workpiece elastic and plastic distortion during clamping and machining;
3) Workpiece movement due machining.

The evaluation method was established based on the measurement of datum displacement, which was calculated by coordinate system transformation. Coordinate frame transformation can be presented by vectors in order to analyse the effect of fixturing errors to the machined surface error. The fixture performance was assessed quantitatively from the measurement results, which provided critical information for fixture improvement.

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References
