An On-line Measurement Technology for Large Surface

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Abstract. In this paper, we offered an on-line measurement method for large curved surfaces with the principle of linkage between the manufacturing equipment and the common measuring machine CMM. An on-line standing measurement system for large curved surfaces shaped by sandblast machine developed with this measurement method is introduced in this paper, include its measurement principle, establishment and conversion to working coordinates, measuring process and coordinates match method with rotating angles and moving distances individually optimized.

1. Introduction
Presently, along with the development of manufacturing, especially the development of automobile, avigation, spaceflight and watercraft, mechanical parts with large curved surfaces are used more and more. There are many troubles in machining and measuring these parts, such as large, distorting easily, loading and unloading difficultly, benchmark hard confirmed, evaluating difficultly and so on.

Aiming at the measurement of the large curved surfaces, the conventional method is making special truss templates or special large-scale measuring equipment. But, it’s hard to assure the precision of these vast equipments and the superposition of the processing benchmark and measuring benchmark. Also, it’s expensive to make these special equipments, and they can’t fit different curved surfaces commendably.

To conquer the former troubles of the conventional measurement method, in this paper, we offered an on-line measurement method with the principle of linkage between the manufacturing equipment and the common measuring machine CMM. We have developed an on-line standing measurement system for large curved surfaces shaped by sandblast machine with this method. In this paper, the on-line measurement system is used as the example to describe the measurement method. A coordinates match method with rotating angles and moving distances individually optimized is also offered.

2. Measuring objects and measurement principle
The objects of the on-line measurement system for large curved surfaces shaped by sandblast machine contain more than ten kinds of large thin parts with curved surfaces (length: 7~15m, width: 0.5~2.3m, arc height: 50~400mm, thickness: 3~10mm). Surfaces of parts are complicated hyperboloid, and there are distortions at landscape orientation. While being sandblasted, they are hung upright on slipping shelf of sandblast machine which can be moved landscape orientated.
The measurement system is shown in figure 1. Its main body is CNC Coordinate Measuring Machine (CMM) which is fixed on the spot of sandblast process. Slipping shelf of sandblast machine can also be regarded as the part fixing tool for measuring machine matched with special equipments used for adjusting and mooring, together with an assistant X’ axis (scale: 1500 mm) that can record the moving distance of the slipping shelf accurately consist other member of the system.

After shaped by sandblast machine, the curve-surface parts can be moved to measuring position by motion of the slipping shelf. Measurement to the parts can be carried out after simple adjusting without assembled nor unassembled.

The scale of CMM is 1700 mm × 2500 mm × 680 mm. The maximum length at X direction of curve-surface parts to be measured is 15 m. If positions to be measured exceed measuring scale of the machine in the process, slipping shelf is moved to make sure the positions can be translated into effective scale. And the moved distance should be recorded by raster of the assistant X’ axis. After corresponding conversion to the working coordinate system using the recorded distance, the X axis of sandblast machine and X axis of CMM will be consolidated to one working coordinate system.

3. Establishment and conversion to working coordinate system
Before establishing working coordinate system, the theoretical coordinate system should be established on the design model in CAD system to pick up the characteristic points. With the points on the part corresponding to these characteristic points as benchmarks, the working coordinate system can be established. Existence of the deviation between working coordinate system and theoretical one will bring a great system error to the measure result. So we should do our possible to establish the working coordinate system meet to the theoretical one.

Set a typical surface as an example to illustrate the establish process of working coordinate system, shown in Figure 2.
In the establish process of the working coordinate system, if the plane and line as benchmarks are too small, the errors of them will be amplified. In this measuring system, the benchmark has been chosen on the surface as extensive as possible. Plane1 determined by PNP1, PNP2, and PNP3 in Figure 2 is considered as the benchmark plane XOY. Fitting line of the projection of the straight edge Line2 in Plane1 as the X axis, intersection of Line1 and Line2 projection in Plane1 as the origin O, coordinate system XYZ can be established shown in the picture.

To make sure coincide of PNP1, PNP2 and PNP3, an original coordinate system X’Y’Z’ should be established at first in factual process. XOY of the measuring machine is recognized as X’O’Y’ plane. Fitting line of the Line2 projection in Plane1 is the X’ axis, intersection of Line1 and Line projection in Plan1 is the origin O’. With the auto-finding function of CMM, get PNP1, PNP2 and PNP3 in the coordinate system X’Y’Z’, and then precise coordinate system XYZ can be established.

Deviation exists in benchmarks because of processing error leads to deviation between coordinate system on theoretical model and on actual parts. Some deviation was brought in because of deviation between X’O’Y’ and XOY, when PNP1, PNP2, PNP3 were got in the original coordinate system X’Y’Z’. After practice, it can be found that measurement location is accuracy at the working coordinate system established in this way, and can also meet the requirement. The minor deviations can be eliminated through coordinates match (details can be seen in 5).

4. Measuring process of lines on curved surface
The measurement to curved-surface parts is finished by measuring special lines on the surface. The lines which are cross-sections of the surface are planar. In this system, one-dimensional scanning probe does a continuous job to the lines. The track of measuring machine in XOY plane is linear. Z axis moves through the feedback of inductance probe, make sure probe to slide on the surface with certain force. At the same time, the measuring system gets the coordinates of center of the probe in a distance of fixed interval.

The design data distilled from theoretical mathematical model is transmitted into the software for measuring system. After the same coordinate system to the one for distilling the data has been established, measuring trails to different lines to be measured can be planned according to the input design data by the trails-planning models in system software. Measurements to the lines process to the programming route. If the lines are in the measuring scale of the machine, measurement can be finished by the movement of it; else if they are out of its scale, slipping shelf of sandblast machine is moved to make the lines fit the measuring scale, and the moved distance is recorded by assistant axis X’ while corresponding conversion to the working coordinate system. Then the measurement goes on; repeat in this way, the whole process would be finished. As the move of slipping shelf is just a parallel movement in X direction, and the distance is recorded by raster of X’, so with the record of X’ the conversion can be finished at corresponding direction.

If a line to be measured is out of the measuring scope, measurement can continue on several sections divided owing to actual situations and sections should be partly overlapped. With Data Registration Software in the system, a whole line can form by registration of all the sections.
5. Evaluation for special lines and surface

All the lines on the curved surfaces to be measured in this measurement system are planar. Therefore, these lines is evaluated with the two coordinates (Y, Z), it also can be the (X, Z) in certain instance.

The data acquired by CMM are the coordinates of trails of the probe ball center. The radius of the probe ball must be compensated to these data before evaluated. After design data \((y_{sj}, z_{sj})\) and measure data \((y_{mi}, z_{mi})\) have been fitted to smooth lines, the measure line rotates certain angle and moves certain distances to eliminate the system error caused by not coincide of these two coordinate systems. Then the errors \(e_i\) on corresponding points of the two lines in Z direction can be calculated.

5.1. Compensating the radius of probe ball

Interpolate the center coordinates \((y_i, z_i)\) of probe ball to smooth line with cubic spline interpolation, calculate the normal vectors \((y_{yi}, z_{yi})\) of \((y_i, z_i)\), envelop this line with the radius using equation (1), and the compensated coordinates \((y_{mi}, z_{mi})\) will be acquired.

\[
\begin{align*}
y_{mi} &= y_i - r \cdot y_{yi} \\
z_{mi} &= z_i - r \cdot z_{yi}
\end{align*}
\]  

5.2. Coordinates match

The coordinates match method to the planar lines: optimization for measure line is executed with rotating angle as parameter and the cosine sum of angles between normal vectors of corresponding points on the measure line and design line as performance function at first. Rotate the measure line with the optimal angle acquired from the optimization, and measure line will parallel with design line; After that, optimization for rotated measure line is executed with moving distances in X and Y as parameters and the standard deviations of Z between the measure line and design line as performance function. Move the rotated measure line with the optimal distances, and the match process is completed.

The following is the detailed match method.

5.2.1. Calculating the optimal rotating angle.

At first, the normal vectors \(v_{si}\) and \(v_{mi}\) corresponding to the points on the design line and the measure line interpolated with cubic spline interpolation should be calculated.

Set \(\theta_i\) as the angles between corresponding normal vectors corresponding to the two lines when the rotating angle of measure line is \(\delta\). There are relations like equation (2):

\[
F(\delta) = \sum_i \cos \theta_i = \sum_i v_{si} \cdot (A v_{mi})
\]  

Here:

\[
A = \begin{pmatrix}
\cos \delta & \sin \delta \\
\sin \delta & -\cos \delta
\end{pmatrix}
\]

In case \(\theta_i\) are all acute angles, the optimization target is transfer to minimum of \(\sum_i \theta_i\) or maximum of \(F(\delta)\). \(\delta_{opt}\) which make \(F(\delta)\) to maximum is the optimal angle known from equation (2).

Set \(\alpha_{si}\) and \(\alpha_{mi}\) as the angles between \(v_{si}\) and X axis and \(v_{mi}\) and X axis, the equation (2) can be transferred to equation (3):

\[
F(\delta) = \sqrt{M^2 + N^2} \sin(\beta + \delta)
\]
\[ M = \sum_i \cos(\alpha_{si} - \alpha_m) \]
\[ N = \sum_i \sin(\alpha_{si} - \alpha_m) \]

Here:
\[ \sin \beta = \frac{M}{\sqrt{M^2 + N^2}} \]
\[ \cos \beta = \frac{N}{\sqrt{M^2 + N^2}} \]

\( \delta_m \) can be confirmed easily from equation (3). The rotated coordinates \((y_{ri}, z_{ri})\) with \( \delta_m \) is calculated by equation (4)
\[
\begin{pmatrix}
   y_{ri} \\
   z_{ri}
\end{pmatrix} = \begin{pmatrix}
   \cos \delta_m & \sin \delta_m \\
   -\sin \delta_m & \cos \delta_m
\end{pmatrix}\begin{pmatrix}
   y_m \\
   z_m
\end{pmatrix}
\]

\((4)\)

5.2.2. Calculating the optimal moving distances. In the rotating process in 5.2.1., the coordinates of the measure line are changed, too. It’s necessary to move the measure line approximately before optimization for the optimal moving distances. In this paper, we use the distances between barycenters of the design line and the rotated measure line as the approximate moving distances. Move the rotated measure line, and the coordinates \((y_{ti}, z_{ti})\) will be acquired.

The next task is to seek the optimal distances. Because the gradient of the performance function can be calculated expediently, we use the amendatory gradient optimization.
\[ F(\delta_y, \delta_z) = \sum_i (z_{si} - (z_{pi} + \delta z))^2 \]
\((5)\)

Here:
\[ z_{pi} = \text{spline}(y_{si} + \delta_y, z_{si}, y_{si}) \]

\(z_{pi}\) are corresponding to \(y_{si}\) after \((y_{ri}, z_{ri})\) have moved \(\delta_i\) in Y. The \(\delta_{ym}\) and \(\delta_{zm}\) will be the optimal distances in Y and Z which make \(F(\delta_y, \delta_z)\) minimum.

The optimal distances are hunted in the direction in which the performance function decreases most rapidly - the negative of the gradient. One iteration of this algorithm can be written like equation (6):
\[
\begin{pmatrix}
   \delta_y^{(k)} \\
   \delta_z^{(k)}
\end{pmatrix} = -t_k \begin{pmatrix}
   \frac{dF}{dy_{si}} \\
   \frac{dF}{dz_{pi}}
\end{pmatrix}
\]
\((6)\)

After entering (6) to (5), \(t_k\) to make \(F(\delta_y, \delta_z)^{(k)}\) minimum can be calculated with quartering one-dimensional optimization as \(k\leq 2\). In case of \(k>2\), gradient optimization can be amended with parallel tangent principle to expedite the convergent rate. Then one iteration of this algorithm can be written like equation (7):
\[
\begin{pmatrix}
   \delta_y^{(k+1)} \\
   \delta_z^{(k+1)}
\end{pmatrix} = -t_k + \alpha \begin{pmatrix}
   \delta_y^{(k)} \\
   \delta_z^{(k)}
\end{pmatrix} - \begin{pmatrix}
   \delta_y^{(k-2)} \\
   \delta_z^{(k-2)}
\end{pmatrix}
\]
\((7)\)

Iterate former process, and the \((\delta_{ym}, \delta_{zm})\) to make \(F(\delta_y, \delta_z)\) minimum will be acquired. \((y_{fi}, z_{fi})\), the final results for coordinates match, will be achieved after moving \((y_{si}, z_{si})\) with \((\delta_{ym}, \delta_{zm})\), shown in equation (8)
\[
\begin{pmatrix}
   y_{fi} \\
   z_{fi}
\end{pmatrix} = \begin{pmatrix}
   y_{si} + \delta_{ym} \\
   z_{si} + \delta_{zm}
\end{pmatrix}
\]
\((8)\)

5.2.3. Results before and after coordinates match. The change of errors between before and after coordinates match is shown by the following table 1. It’s obvious that the coordinates match method
offered in this paper availably eliminated the system error caused by not coincide of these two coordinate systems and improved the measure precision.

Table 1. The change of errors between before and after coordinates match.

| Index | Y (mm) | Errors in Z before match(mm) | Errors in Z after match(mm) |
|-------|--------|------------------------------|-----------------------------|
| 1     | -85.0000 | 0.0092                      | 0.0022                      |
| 2     | -32.7778 | 0.0081                      | 0.0025                      |
| 3     | 19.4444  | 0.0064                      | 0.0023                      |
| 4     | 71.6667  | 0.0042                      | 0.0017                      |
| 5     | 123.8889 | 0.0016                      | 0.0009                      |
| 6     | 176.1111 | -0.0012                     | -0.0002                     |
| 7     | 228.3333 | -0.0040                     | -0.0013                     |
| 8     | 280.5556 | -0.0066                     | -0.0024                     |
| 9     | 332.7778 | -0.0089                     | -0.0034                     |
| 10    | 385.0000 | -0.0108                     | -0.0041                     |

It’s proved in practice that this coordinates match method with rotating angles and moving distances individually optimized improves the calculating efficiency greatly and reduce the difficulties to construct arithmetic, compared with the conventional methods that use rotating angles and moving distances as parameters and the standard deviation between design data and measure data as performance function.

The surface is reconstructed by measured lines with the method of NURBS surface interpolation. The process of compensating the radius of probe ball and coordinates match for reconstructed surface is similar to the process for lines. It’s no need to discuss here repeatedly.

6. Conclusion
The on-line standing measurement system for large curved surfaces shaped by sandblast machine with the principle of linkage between the manufacturing equipment and measuring machine realized on-line measurement to various large surfaces. In this system, machining and measurement shared the same benchmark, so errors caused by un-superposed benchmark and re-loading can be avoided. Efficiency and accuracy of measure has been improved greatly. Evaluation to the lines on the surface and the surface reconstructed by these lines can be finished by the coordinates match method that optimization to rotating angles and moving distances individually. In this way, the system error caused by not coincide of coordinate systems can be eliminated availably. The measurement system has been used in the enterprise who entrusted us to develop it. The whole measure precision can reach 0.012 mm per 500 mm which is far over actual requirement of surface accessories.

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