Improving Clamping Accuracy of Thin-walled Workpiece in
Turning Operation

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Abstract. This study presents theoretical and experimental error analysis and avoidance which results from the fixation of a thin-walled metal disk workpiece on a duplex turning machine. The distance between the rotating workpiece surface and a fixed datum point is measured using a laser displacement sensor (LDS). The measured data are analyzed numerically to get the error in the fixation system in terms of Euler angles. Then the workpiece clamping points are axially adjusted according to the calculated angles. Moreover, the problem formulation and the solution procedures are presented in details. Finally, a case study has been used to verify the proposed approach. The results indicate that the proposed technique can be used to decrease the fixation error to a reasonable range.

1. Introduction
The machining of complex components such as thin disk-shaped workpieces has been one of the most challenging problems of manufacturing engineering. However, there has been little research about this problem. Research done to date has focused on thermal analysis, dynamic analysis and workpiece deflection during turning operations [1-4].

Currently, a strong need exists to improve the accuracy and surface integrity of such components [5]. Clamping cylindrical workpieces on the turning machine must achieve sufficient accuracy to prevent occurrence of shape and position deviation of the workpiece, hence dimensional and form accuracy of the machined components will be increased [6]. Compared to the rapid progress in the performance of machine tools, the advancement in the performance of chucks was very slow with little available research results [7]. Due to faster advance in the performance and accuracy of machine tools, clamping become the greatest weakness and a bottle neck in any machine processing system[8]. If clamping is not sufficiently accurate undue deviations in the shape and position of the work-pieces may ensue. Deviations in position between the machined and non-machined surfaces of the workpieces are caused by deviations in the alignment between the axis of the workpiece and the axis of rotation of the chuck[9]. The poor form accuracies of the finished workpiece were mainly due to the inaccuracies in the conventional chucking, which allow the pre-existing errors to propagate to the workpiece in the subsequent machining operation[10]. Compared to the rapid progress in the
performance of machine tools, the advancement in the performance of chucks was very slow with little available research results[7].

Byun and Liu develop a method for improving chucking accuracy [11]. All the major factors that affect the positioning accuracy and repeatability of a chucked workpiece have been identified by error budgeting and systematic measurements. Moreover, The effect of kinematic redundancy on chucking, especially, on the positioning accuracy of a cylindrical workpiece has been investigated[12]. In general, chucking error may represent all sorts of errors caused by chucking operation in a broad sense; the chucking error of a workpiece conventionally represents the deviation in the position of the workpiece due to inaccurate chucking [9, 11].

To the best of the author’s knowledge, all literature work was focused on study of cylindrical workpieces clamping and no previous work treat the chucking error of thin walled workpieces. This paper presents a novel study to improve chucking accuracy for such workpieces.

2. Objective and approach

The main aim of this study is to minimize the fixation error of a thin-walled circular workpiece. The paper was organized as follows. Firstly, it is important to formulate the relation between the workpiece orientation angles (Euler angles) and the axially displacements of the fixation points. Secondly, the axial displacement of the rotating workpiece surface is obtained using LDS based measurement system. Finally, a novel approach will be proposed to correlate the LDS measured data to the orientation angles in order to get the relative axially displacements of the fixation points which guarantee the coaxial fixation of the workpiece.

3. Mathematical formulation

For the purpose of the problem formulation the thin disk under study is considered to be a rigid body with a planar surface. The disk is rigidly attached to the inner ring of the bearing on a lathe machine through three points A, B and C on the dashed circle as shown in Fig. 1 (b). These three points define the fixation plane. A world coordinate system O(X, Y, Z) is fixed at the bearing center to the disc at its center O, i.e., the dashed circle center, with Z axis normal to the fixation plane. Due to the fixation error, the geometric center of the disk $O_r$ does not coincide with the rotation center $O$.

It is noted that location of $O$ is unknown as the bearing has been embedded in the machine thus could not be measured directly. Let $i$, $j$ and $k$ denote three unit vectors pointing along the coordinate axis of the world frame $O$, and $m$, $n$ and $\omega$ denote three unit vectors pointed along the rotation coordinate frame. The three unit vectors $m$, $n$ and $\omega$ can be expressed in the world frame $O$ as follows:

$$[m \ n \ \omega] = [i \ j \ k] \begin{bmatrix} c\theta & -s\theta & 0 \\ s\theta & c\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c\varphi & 0 & s\varphi \\ 0 & 1 & 0 \\ -s\varphi & 0 & -c\varphi \end{bmatrix}$$

(1)

where $\varphi$ and $\theta$ are rotation angles of the rotation coordinate frame about $Z$ and $Y$ axes, respectively and, $c\varphi$ is a shorthand notation for $\cos(\varphi)$, $s\varphi$ for $\sin(\varphi)$, $c\theta$ for $\cos(\theta)$ and $s\theta$ for $\sin(\theta)$.

Then the actual rotational axis of the lathe is given by:

$$\omega = i \cos \theta \sin \varphi + j \sin \theta \sin \varphi + k \cos \varphi$$

(2)

If $\varphi$ and $\theta$ are known, then the offsets of the clamps $A$, $B$ and $C$ are given as:

$$u_a = R s \varphi c (\theta), \quad u_b = R s \varphi c (\theta - \frac{\pi}{2}),$$

$$u_c = R s \varphi c (\theta - \frac{\pi}{2})$$

(3)

where $u_a$, $u_b$ and $u_c$ are the clamping offset at $A$, $B$ and $C$ respectively and $R$ is the radius of the bearing inner ring which can be obtained from the specification sheet of the clamping system.
Defining another cylindrical coordinate at \( O \) with the same \( Z \) axis, any point on the fixation plane can be denoted as \((r, \theta, 0)\). As the LDS monitors the part motion at a fixed position, its measurement (along the direction of rotating axis) is obtained by:

\[
u_i(t) = r_i s(\phi) c(\theta - \Omega t_i) \tag{4}\]

Where \( u_i(t) \) is a measured data point for a certain data index \( i \) at a certain time \( t_i \), \( r_i \) is the measured data radius in mm and \( \Omega \) is the angular velocity in rad/sec about \( \omega \) axis. Equation (4) can be extracted using trigonometric relationships, and then the distance equation can be mathematically expressed as:

\[
u_i(t) = r_i s(\phi) [c(\theta) c(\Omega t_i) + s(\theta) s(\Omega t_i)] \tag{5}\]

At another measured date index, i.e. at \( (i+1) \), (1) can be expressed as follows:

\[
u_{i+1}(t_{i+1}) = r_{i+1} s(\phi) [c(\theta) c(\Omega t_{i+1}) + s(\theta) s(\Omega t_{i+1})] \tag{6}\]

In order to get the value of \( \phi \) and \( \theta \), (5) and (6) should be solved simultaneously. However, since \( t_i \) is not equal to \( t_{i+1} \), so the solution of these two equations might not be achieved. So that the most challenging problem faced the authors is to timing \( t_i \) and \( t_{i+1} \) to be the same. The methodology used to achieve that will be briefly described in the next section. For the moment, \( t_i \) and \( t_{i+1} \) are considered to be the same.

Subtracting (5) from (6) yields

\[
\Delta u(t_i) = d_i \left[ s(\phi) c(\theta) + s(\theta) s(\Omega t_i) \right] \tag{7}
\]

where \( \Delta u(t_i) = u_{i+1}(t_{i+1}) - u_i(t_i) \) and \( d_i = t_{i+1} - t_i \)

let \( A = s(\phi) c(\theta) \) and \( B = s(\phi) s(\theta) \) Equation (7) can be written as:

\[
\frac{\Delta u(t_i)}{d_i} = c(\Omega t_i) A + s(\Omega t_i) B \tag{8}
\]

The above equation can be put in the matrix form as:

\[
\begin{bmatrix}
  c(\Omega t_i) & s(\Omega t_i) \\
  c(\Omega t_{i+1}) & s(\Omega t_{i+1}) \\
  \vdots & \vdots \\
  c(\Omega t_i) & s(\Omega t_i)
\end{bmatrix}
\begin{bmatrix}
  A \\
  B
\end{bmatrix}
= \begin{bmatrix}
  \Delta u(t_i) \\
  \Delta u(t_{i+1}) \\
  \vdots \\
  \Delta u(t_i)
\end{bmatrix} \begin{bmatrix}
  d_i \\
  d_i \\
  \vdots \\
  d_i
\end{bmatrix} \tag{9}
\]

or equivalently,

\[
\Psi \Pi = \Delta \tag{10}
\]

then

\[
\Pi = \left(\Psi^T \Psi\right)^{-1} \left(\Psi^T \Delta\right) \tag{11}
\]

Once we get the value of \( \Pi \), \( \phi \) and \( \theta \) can be found as follows:

\[
\phi = \sin^{-1} \left( \|\Pi\| \right) \tag{12}
\]

\[
\theta = a \tan^{-1} \left( \frac{A}{B} \right) \tag{13}
\]

### 4. Experimental setup

The experimental set-up to measure the deviation of the workpiece surface from a certain datum is shown in Fig.1(a). The workpiece is fixed on the lathe machine by the three clamps. These clamps are
rigidly attached on the inner ring of the bearing of the machine. Deviation quantity is estimated utilizing LDS with no contact achieved. Commercial LDS (LK-HD500) of diffuse reflection type is used. The wave length of its light source is 650 nm with spot diameter at reference distance approximately 300 μm. More detailed specification can be found in [13].

![Experimental setup and coordinate frames](image)

**Figure 1.** a) Experimental setup [14]; b,c) Coordinate frames

5. Illustrative example

The proposed model is illustrated by a thin-walled titanium disk workpiece fixed on the experimental setup which briefly discussed in the previous section. The disk dimensions are 300 mm outer diameter and 6.6 mm thickness. The workpiece surface roughness is limited to 0.05 mm. The workpiece is rigidly fixed on the machine clamp assembly at points A, B, and C. LDS is used to measure the axial deviation of the workpiece surface from the vertical plane. The measured data (Fig.2) divided into three main portions. At the beginning, the motor should be still for a few seconds to detect the axial displacement of a reference point at a radial distance equal to \( r_{i_1} \), which will be used as a datum point for the periodic measured data (Portion A). After that, the motor starts up with large fluctuation (Portion B). Then the motor rotates at approximately constant speed with a little fluctuation (Portion C). After complete the upper measurement sequence the motor is stopped and the disk is turned back to the same reference point. Then the LDS is moved radially a distance equal to \( d_i \) toward the center of the disk. A new data set measured starting from a new reference point which locates at \( r_i \). These procedures are repeated until we get sufficient data sets.

To achieve adequate analysis of these data sets the following steps have been followed:

1) Data smoothing using Gaussian function, which is defined in terms below, in order to spread the data noise at each point over a predefined area.

\[
 g(x) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}
\]

where \( \sigma \) is standard deviation, \( \mu \) is mean and \( x \) is data point.

2) Determine the displacement value at the reference point by calculating the mean of the measured data within ‘Portion A’, see (Fig.2 (a)).
3) Locate the starting point of each periodic cycle (the point with the same displacement of the reference point).
4) Calculate the actual rotating speed of the motor $\Omega$ within ‘Portion C’.

$$\omega = \frac{2\pi}{T}$$

(15)

where $T$ is the periodic time, which can be calculated by knowing of the LDS measuring frequency and the number of data inside one complete cycle.
5) Beginning from the reference point of the periodic cycle of two different measured data, calculate $\Delta u(t_i)$.
6) Finally, calculate clamps offsets $u_a$, $u_b$ and $u_c$ using (3).

These steps have been applied to a workpiece in-hand. The measured data before and after data smoothing are shown in Fig.2 (b).

Fig. 2 (c) shows two different in-phase data sets (measured data at different radius) with different amplitudes and zero phase shift. The difference between two waves $\Delta u(t_i)$ is also plotted in the same figure.

Fig. 2 (d) shows the axial deviation of the disk surface from the vertical plane measured at the outer diameter of the disk, and hence this is considered to be the maximum deviation. It can be seen that deviation amplitude is approximately 1.2 mm. After the experiment was executed the deviation amplitude decreased from 1.2 mm to less than 0.2 mm. However, this amplitude (0.2 mm) is still larger than the target deviation (0.1 mm). Moreover, the insight into Fig. 2 (d), the measured data reveals that the deviation fluctuates from 0.19 mm to 0.26 mm (the maximum deviation 0.07 mm) for 85% of each cycle (green rectangle). And for the remaining 15% of the cycle the deviation increased very quickly to reach 0.2 mm (red rectangle). This increasing may be resulted from some inherent flatness defects in the workpiece in this portion. Therefore, 0.2 mm is considered to be reasonable for the investigated disk. (0.2mm > 0.1mm+0.05mm, not reasonable yet).

**Figure 2.** a) Portions of measured data; b) Data smoothing; c) In-phase data sets; d) Measured data before and after adjustment
6. Conclusion
Fixation system for thin disks on turning machine must fulfill a precise rigid fixation during machining operation. However, current fixtures systems do not guarantee coaxial fixation of the workpiece on the turning machine bearing, which may be result in workpiece damage. Hence, a novel approach is proposed to handle this problem. Experiments are executed to verify the proposed approach. The experimental results show high accuracy of the fixation system with a reasonable deviation.

Reference
[1] Cheung E, Yuan W and Hua M 1999 Physical Simulation of the Deflection in Turning of Thin Disk-Shaped Workpieces The International Journal of Advanced Manufacturing Technology 15 863-8
[2] Guo J, Lee K-M, Wuguang L and Bo W 2015 Design Criteria Based on Modal Analysis for Vibration Sensing of Thin-Wall Plate Machining Mechatronics, IEEE/ASME Transactions on 20 1406-17
[3] Elsheikh A H, Guo J and Lee K-M 2019 Thermal deflection and thermal stresses in a thin circular plate under an axisymmetric heat source Journal of Thermal Stresses 42 361-73
[4] Elsheikh A H, Guo J, Huang Y, Ji J and Lee K-M 2018 Temperature field sensing of a thin-wall component during machining: Numerical and experimental investigations International Journal of Heat and Mass Transfer 126 935-45
[5] Salman K h, Elsheikh A H, Ashham M, Ali M K A, Rashad M and Haiou Z 2019 Effect of cutting parameters on surface residual stresses in dry turning of AISI 1035 alloy Journal of the Brazilian Society of Mechanical Sciences and Engineering 41 349
[6] Koepfer C 1996 Four considerations for selecting chucks and arbors Modern Machine Shop 69 88-94
[7] Donmez M A, Blomquist D S, Hocken R J, Liu C R and Barash M M 1986 A general methodology for machine tool accuracy enhancement by error compensation Precision Engineering 8 187-96
[8] Ema S and Marui E 1994 Chucking Performance of a Wedge-Type Power Chuck Journal of Engineering for Industry 116 70-7
[9] Pahlitzsch G and Hellwig W 1968 Advances in Machine Tool Design and Research 1967, ed S A Tobias and F Koenigsberger: Pergamon) pp 97-118
[10] Byun J 2003 Methods for Improving Chucking Accuracy of a Cylindrical Workpiece in Finish Hard Turning. (United States -- Indiana: Purdue University)
[11] Byun J and Liu C R 2012 Methods for Improving Chucking Accuracy Journal of Manufacturing Science and Engineering 134 051004-
[12] Byun J and Liu C R 2008 Improving Chucking Accuracy and Repeatability by Reducing Kinematic Redundancy. In: 3rd JSME/ASME International Conference on Materials and Processing. (Evanston, Illinois, USA: ASME )
[13] Keyence http://www.keyence.co.uk/.
[14] Bai K, Qin J, Lee K-M and Hao B 2019 Design and chatter prediction analysis of a duplex face turning machine for manufacturing disk-like workpieces International Journal of Machine Tools and Manufacture 140 12-9