On-line Data Analysis and Optimization of Crankshaft Dynamic Balance

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Abstract. The crankshaft is a high-speed rotating component that is widely used in many fields. Dynamic balance of the crankshaft is an important process stage that affects the quality of the crankshaft. In order to optimize the quality of crankshaft dynamic balance machining, this paper illustrates the importance of the initial unbalance of crankshaft to the dynamic balance machining of crankshaft. For the initial imbalance distribution of crankshaft, the improved mean method, gradient descent method and mean shift algorithm are used to calculate the machining center. The position of the hole realizes the crankshaft imbalance correction with different effects and reduces the processing strength of the crankshaft dynamic balance phase. The study is applicable to the machining of crankshafts in geometric centering processes in batches.

Keywords: crankshaft dynamic balance, online control, mean method, gradient descent method, mean shift algorithm

1. Introduction

The crankshaft acts as a rotor and, in the working state, mainly outputs power by rotating motion. Rotor unbalance is a common phenomenon in the rotor. The crankshaft blank produced by the same mold has similar axial mass distribution, crack defects and shaft deformation. As a result, the uneven distribution of crankshaft blanks in the same batch presents a certain deviation trend [1]. The crankshaft roughing stage of the geometric centering process determines a pair of center holes for the machining of the entire batch of crankshafts, thereby determining the initial unbalance of the crankshaft. The initial unbalance is continuously reduced during crankshaft roughing and finishing, and finally the final balance of the crankshaft is used to control the dynamic imbalance within the allowable range. If the unbalanced offset trend can be grasped by sampling analysis, and the better central hole position is found, the unbalance amount entering the final balance of the crankshaft can be as small as possible, so that the crankshaft dynamic balance processing quality can be improved, the crankshaft quality can be improved, and the production cost can be reduced.

2. Crankshaft dynamic balance online quality control

The online control of the crankshaft machining is carried out, and the position of the central hole is adjusted one or more times during the crankshaft machining process to optimize the dynamic balance machining effect of the crankshaft. By collecting the dynamic balance test data of the partially processed crankshaft, the center hole position is analyzed and calculated, and the result is fed back to
the machining process, so that the subsequent machining effect is improved. The application of reasonable online control technology can further improve the processing quality in the final equilibrium stage, which is conducive to actual production. During the crankshaft machining process, the initial unbalance amount is a dynamic change [2], which is shown in Figure 1, which is $U_0$ in the roughing process, $U_1$ in the roughing process, and $U_2$ in the finishing process. $U_2$ is necessary for the final equilibrium phase. $U_2$ data analysis is the best and no additional acquisition is required. The crankshaft online system operating mode can be represented by Figure 2:

Figure 1. Initial imbalance of the crankshaft

3. Crankshaft dynamic balance analysis and optimization

3.1 Crankshaft dynamic imbalance distribution trend

The center hole position of the traditional geometric centering process is centered at the geometric center or the mean center of the sampled crankshaft [3]. The data points in the standard coordinates are used to describe the offset of the unbalance on the end face of the crankshaft. The mean center of the sample number $n$ is calculated as:

$$\begin{align*}
    x &= \frac{\sum_{i=1}^{n} x_i}{n} \quad (n = 1, 2, ..., n) \\
    y &= \frac{\sum_{i=1}^{n} y_i}{n} \quad (n = 1, 2, ..., n)
\end{align*}$$

Figure 2. Crankshaft online quality control mode

The result is greatly affected by the randomness of sampling. It is necessary to ensure that the number of samples is sufficient to stabilize the results; and the data does not exclude sample points that deviate from the expected value, and the accuracy of the results is insufficient. Figure 3. shows the frequency distribution of the imbalance of the entire batch of crankshafts on the two end faces.
The mean method is improved, and data noise filtering is added [4] to enhance the stability and accuracy of the results. Round with the mean center\((O_x, O_y)\), \(R\) is the maximum dynamic balance offset, the radius of the \(R_f\) split circle, and \(k\) is the filter strength:

\[
(x - O_x)^2 + (y - O_y)^2 = R_f^2
\]  

(2)

\[
R_f = (1 - k) \cdot R \quad (0 \leq k < 1)
\]  

(3)

The mean center is recalculated according to the data points in the circle, and the updated mean center has a certain offset from the original mean center. As shown in the histogram, when the filter intensity \(k=0.5\), as shown in Figure 4, the mean center of the \(k\) value is taken as 0.5. the data points with a large offset of about 5% can be filtered, the calculated mean center is represented by a green dot, and the semi-transparent area indicates the range of the noise data; \(\bar{\text{B}}\) represents the old mean center.

**Figure 3.** The frequency distribution of the imbalance of the entire batch of crankshafts on the two end faces

**Figure 4.** The mean center of the \(k\) value is taken as 0.5

### 3.2 Dynamic balance analysis based on gradient descent method

To minimize the machining of the crankshaft balance and the shortest machining time, the gradient hole method can be used to calculate the center hole position[5]. The gradient essence is a vector, and the function has the largest rate of change along the gradient direction. In the sampled data points, the sum of the Euclidean distances of the central hole and all data points can represent the sum of the unbalanced quantities of the sampled samples[6]. The loss function of the crankshaft dynamic balance problem can be defined as:

\[
\min f(x, y) = \min \sum_{i=1}^{n} \sqrt{(x_i - x)^2 + (y_i - y)^2}
\]  

(4)

Then the gradient can be expressed as the gradient descent method uses the negative gradient direction as the direction of the iteration:

\[
\nabla f(x, y) = \left( \frac{x - x_i}{\sqrt{(x - x_i)^2 + (y - y_i)^2}}, \frac{y - y_i}{\sqrt{(x - x_i)^2 + (y - y_i)^2}} \right)^T
\]  

(5)

The equation of the gradient descent method can be expressed as follows, where \(\theta_i\) represents the current point and the updated point, \(\alpha\) represents the step size, and \(J(\theta)\) represents the loss function:

\[
\theta_i = \theta_i - \alpha \frac{\partial}{\partial \theta_i} J(\theta)
\]  

(6)

The unbalanced amount of the entire batch of crankshafts is represented by a scatter \(t\), the forward path of the iterative result is indicated by a black trajectory, and the central hole position is
identified by a blue dot. The iterative process and results on both ends of the crankshaft are shown in Figure 5:

![Figure 5 Process and results of calculating the center hole position by the gradient descent method](image)

Since the gradient descent method is a global search algorithm, it is necessary to increase the number of samples to reduce the influence of sampling randomness on the results. After repeated experiments, the number of samples reached 200 or above can make the calculation results better. As shown in Table 1, only some calculation results are listed. Generally speaking, the gradient descent method has smaller $\overline{D}$ and larger $\Delta D$ than the improved averaging method. It gets a smaller amount of imbalance and the correction is better:

| Magnitude | Improved mean algorithm | Value of $\overline{D}$ [g*cm] | Value of $\Delta D$ [g*cm] | Gradient descent center | Value of $\overline{D}$ [g*cm] | Value of $\Delta D$ [g*cm] |
|-----------|-------------------------|-------------------------------|----------------------------|--------------------------|-------------------------------|----------------------------|
| 100       | (-8.908, -20.154)       | 54.674                        | 6717.1                     | (-8.74, -20.758)         | 54.715                        | 6594.9                     |
| 100       | (-8.156, -15.729)       | 54.481                        | 7292.2                     | (-8.806, -12.81)         | 54.567                        | 7035.9                     |
| 200       | (-9.286, -18.234)       | 54.576                        | 7009.1                     | (-7.59, -15.806)         | 54.471                        | 7322.0                     |
| 200       | (-5.103, -18.163)       | 54.559                        | 7059.8                     | (-6.432, -15.412)        | 54.470                        | 7325.0                     |
| 300       | (-9.994, -15.549)       | 54.557                        | 7065.7                     | (-7.035, -14.628)        | 54.474                        | 7313.1                     |
| 300       | (-8.776, -16.672)       | 54.508                        | 7211.7                     | (-6.130, -16.662)        | 54.485                        | 7280.3                     |

3.3 Dynamic balance analysis of crankshaft based on mean shift algorithm

To obtain a larger number of small unbalanced crankshafts and improve the first pass rate of crankshaft machining, the center shift position can be calculated using the mean shift algorithm to improve the distribution of crankshaft unbalance.

In the N-dimensional space, there are k sample points in the high-dimensional sphere region $S_h$ with bandwidth h, and the basic vector form of the mean offset is:

$$M_h(x) = \frac{1}{k} \sum_{i \in S_h} (x_i - x)$$

(7)

The Gaussian kernel function is introduced to participate in the calculation, so that the contribution of the data points closer to the current point is larger at each iteration, and the contribution of the data points farther from the current point is smaller.

$$N(x) = \frac{1}{\sqrt{2\pi h}} e^{-\frac{x^2}{2h^2}}$$

(8)

The vector of the mean shift can be expressed as:

$$M_h(x) = \frac{\sum_{i=1}^{n} G_h(x_i - x) w(x_i)(x_i - x)}{\sum_{i=1}^{n} G_h(x_i - x) w(x_i)}$$

(9)

Where $w(x_i)$ is greater than 0, indicating the weight of each sample; H is the bandwidth matrix:
The averaging offset vector can be expressed as:

\[ \mathbf{H} = \begin{bmatrix} h_1^2 & 0 & \cdots & 0 \\ 0 & h_2^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & h_d^2 \end{bmatrix}_{d \times d} \]

By defining the kernel function and the mean shift function for the iterative update calculation; setting the minimum iteration distance to the most iterative convergence condition; setting the bandwidth adjustment sample point range, you need to take \( h > 10 \) to meet the dynamic balance analysis, \( h \) too small the result is too many sorting categories to determine the center hole position.

The results of the analysis and calculation show that the green dot in the scatter plot indicates the position of the center hole, and the orange dot is the data noise, As shown in Figure 6, we can see that the points around the density center are densely distributed:

![Figure 6. Mean Shift Algorithm Results at 1000 Samples](image)

Since the dynamic balance of the entire batch of crankshafts cannot be obtained in practice, the training algorithm requires a relatively high number of data samples, so the product with a quantity of 200 is evaluated for results. The center hole position of each algorithm is shown in Table 2.

| Center of the A end face | \( D \) value of the A end face [g*cm] | Center of the B end face | \( D \) value of the B end face [g*cm] |
|-------------------------|-------------------------------------|------------------------|-------------------------------------|
| Center of the mean method | (1.316, -21.642) | 55.421 | (-30.967, -7.403) | 52.961 |
| Center of \( k=0.5 \) mean method | (-5.103, -18.163) | 54.559 | (-38.458, -2.616) | 52.374 |
| Center of gradient descent | (-6.432, -15.412) | 54.470 | (-35.722, -1.346) | 52.396 |
| Center of mean shift method | (-7.56, -12.45) | 54.553 | (-31.05, -0.04) | 52.739 |
The mean shift algorithm needs to train the algorithm model, so the number of samples should be increased appropriately. After repeated experiments, the $D$ and $\Delta D$ of the center hole calculated by the mean shift algorithm are not more advantageous than the previous two algorithms, but still have a good correction effect; the result of the algorithm can generally obtain a larger number of imbalances at 50g. Crankshaft within cm, improve the first pass rate of the crankshaft, only listed some results. In Figure 7., the gray figure in the histogram corresponds to the geometric center of the unbalanced frequency distribution, the yellow is the result of the improved mean method, the green is the result of the gradient descent method, blue The result of the mean shift algorithm. Take the results of one of the end faces and plot the frequency distribution as shown in figure 7.: 

![Figure 7. The distribution of the frequency of the entire batch of crankshafts corresponding to the number of samples being 200](image)

4. Conclusions
(a) The mean shift algorithm can obtain better unbalance correction effect, but it is not as good as the former two; it is suitable for a slightly larger number of samples, which requires the central hole to make the crankshaft processing the highest pass rate, and the crankshaft with the highest number of high-quality crankshafts Balance processing.
(b) Gradient descent method can obtain the best unbalance quantity correction effect; it is suitable for crankshaft dynamic balance machining with a small number of samples, minimum required dynamic unbalance, minimum workload and shortest processing time.

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