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An approach to the assessment of cam form

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Abstract

Camshafts play an essential role in the performance of internal-combustion engines. In order to assess the quality of cam form, it is required to match the measured points with the designed geometry, which is provided in terms of either a design function or a nominal data point set. In this paper, an effective method is developed for the case of using the nominal points. A given nominal data point set is reconstructed into a continuous representation of the cam form using B-spline approximation. A nonlinear least squares algorithm is applied to match the measured points with the reconstructed template. The location parameters are estimated by fitting the base circle. A nested approach is adopted to iteratively estimate the projection points and rotation parameter using the Levenburg - Marquardt algorithm. Numerical experiments are conducted to validate the proposed approach. Compared to the iterative closest point (ICP) method, the estimated parameters obtained by the proposed approach are more accurate.

Cam evaluation, B-spline, orthogonal distance fitting, template matching

1. Introduction

As one of the most important components of a combustion engine, the camshaft, is of decisive importance for a good drive quality as well as for the fuel consumption of automobiles. In the quality control of camshaft manufacturing, the dimensional and form deviations of cam profiles need to be evaluated. The design geometry of a cam profile is normally provided in terms of either a series of design functions or nominal points. The cam profile is normally measured by a measuring machine, e.g. coordinate measuring machine or shaft measuring machine. In the paper, an approach to form deviation evaluation is presented for the cam whose design geometry is represented by the nominal points, which are specified by the Cartesian coordinates or a cam stroke diagram with a radius of the base circle.

2. Methodology

In this approach, the nominal points of a cam profile are used to reconstruct a continuous function, which is further used to evaluate the form deviation by the orthogonal distance fitting (ODF). The key procedures are shown in figure 1. Firstly, the template representing the design geometry is reconstructed by the B-spline curves (Figure 1 (a)). Secondly, the position parameter vector $\mathbf{X_o}$ is determined by the base circle fitting (Figure 1 (b)). Thirdly, the template is transformed and consequently the origin of the ideal coordinate system is in accordance with the circle center $\mathbf{X_o}$ (Figure 1 (c)). Lastly, the rotation parameter ϑ and the form deviation are estimated simultaneously by the template matching (Figure 1 (d)).

2.1. B-spline reconstruction

The B-spline curves are constructed as follow: i) parameterization of the nominal data set; ii) knot selection; iii) calculation of basis functions; iv) calculation of control points [1].

Normally, the construction of B-spline curves is implemented in two ways, i.e., interpolation and approximation. If interpolation is chosen to reconstruct the continuous curve, there is no reconstruction error. The control points $\mathbf{C}$ are obtained by a linear system. If approximation is adopted, the reconstruction error should be controlled lower than the level of form deviation. The control points $\mathbf{C}$ are calculated by an ODF algorithm. For both two conditions, the obtained parametric functions $\mathbf{f}(u, \mathbf{C})$ can be used for further calculations.

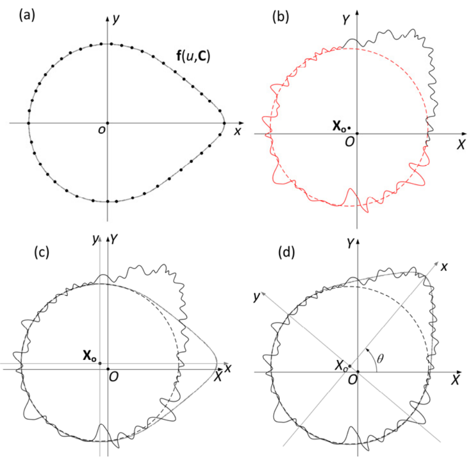

Figure 1. The key procedures of the cam fitting: (a) B-spline reconstruction; (b) base circle fitting; (c) coordinate transformation; (d) template matching.

2.2. Base circle fitting

According to the geometrical characteristics of the cam profile, the location of the cam is defined as the center of the base circle. In such a case, the position parameters could be determined by the base circle fitting.

Before the implementation of the circle fitting, the measured points should be assigned to the base circle and main cam. In this approach, the parameters, such as the radius of the base circle and the starting and ending positions of the base circle are provided as the prior information for the subsequent segmentation.

In order to avoid the influence of noise, form deviation and misalignment between the nominal template and measured points, several measured points at the identified ending area on the base circle are eliminated. In general case, the central angle of the base circle is above 180°, which means the numerical accuracy and stability of the estimated radius and center can still be guaranteed, even though several points have been eliminated. At last, ODF is applied to the base circle [2].

2.3. Coordinate transformation

After determining the center of the base circle, the nominal template is transformed to align its origin with the center of the base circle. Therefore, the nominal template and the measured points are in the same coordinate system.

2.3. Template matching

Finally, the template matching is applied to estimate the parameter ϑ and the form deviation by the ODF. The form deviation is defined as the orthogonal distance from the measured point to the nominal template. The sum of the squares of the deviations is minimum.

$$\min_{\theta} \sum_{i=1}^{m} \left\| \mathbf{X}_i - \mathbf{X}_i' \right\|^2$$

where m is the number of the measured points; $\mathbf{X}_i = (X_i, Y_i)^T$ is the coordinate vectors of the i^{th} measured point; $\mathbf{X}_i' = (X_i', Y_i')^T$ is the coordinate vector of the i^{th} minimum distance point on the model feature, which could be represented by the rotation matrix **R** and the B-spline parametric functions, i.e. $\mathbf{X}_i' = \mathbf{R}^{-1}\mathbf{f}(u_i)$.

The solution of the least squares problem is determined alternately in a nested iteration scheme [3].

$$\min_{\theta} \sum_{i=1}^{m} \min_{u_i} \left\| \mathbf{X}_i - \mathbf{R}^{-1}\mathbf{f}(u_i) \right\|^2$$

The inner iteration finds the projection point of each measured point by using the Gauss-Newton method. The outer iteration updates the rotation parameter ϑ by the Levenburg - Marquardt algorithm. The Jacobian matrices for the inner and outer iterations are provided as follow:

$$J_{d_i, u_i} = -\frac{\left(\mathbf{X}_i - \mathbf{R}^{-1}\mathbf{f}(u_i)\right)^T}{\left\| \mathbf{X}_i - \mathbf{R}^{-1}\mathbf{f}(u_i) \right\|} \mathbf{R}^{-1} \frac{\partial \mathbf{f}}{\partial u_i}, \quad J_{d_i, \theta} = -\frac{\left(\mathbf{X}_i - \mathbf{X}_i'\right)^T}{\left\| \mathbf{X}_i - \mathbf{X}_i' \right\|} \frac{\partial \mathbf{R}^{-1}}{\partial \theta} \mathbf{f}(u_i).$$

3. Numerical validation and discussion

The effectiveness of the proposed algorithm is validated by the numerical experiments. To simulate a cam profile, a four circular arc cam was adopted [4]: the radii were 18 mm, 43 mm, 5 mm and 43 mm, respectively. On the cam profile, a data set $\{\mathbf{x}_i\}_{i=1}^{360}$ was taken as nominal points (sampling interval 1°).

3.1. Reconstruction error

Using the simulated nominal points, the template was reconstructed by B-spline curves. The reconstruction errors were investigated for different numbers of control points. The numbers were 100, 200, 360, and the reconstruction errors of the main cam are shown in figure 2.

The results indicate that when the approximation is adopted, the more control points are utilized, the lower the reconstruction error will be obtained. When the B-spline interpolation is adopted (n = 360), there is no reconstruction error. However, it should be noted that more control points will result in lower efficiency of the subsequent processes.

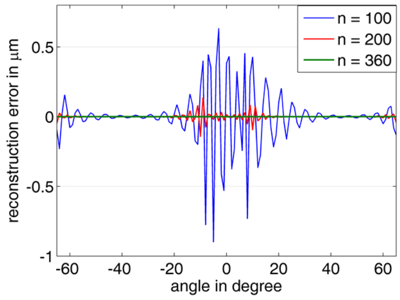

Figure 2. The reconstruction error of the main cam obtained by using the B-spline curves with different numbers of control points, i.e. n = 100, 200, 360.

3.2. Comparison of the ICP and ODF methods

The circular arc cam was resampled with an intended rotation angle error of 0.3°, and the Gaussian noise (σ_o = 1 µm) was superimposed on the sampled points. The iterative closest point (ICP) [5] and the proposed approach are implemented to estimate the rotation and position parameters. The mean absolute error (MAE), root-mean-square error (RMSE) and peak-to-valley (PV) were calculated for error comparison. The process was repeated for 1000 times and the biases and uncertainties associated with the estimated parameters are presented in Table 1.

Table 1 The distributions of the estimated parameters.

Method	X_o (µm)		Y_o (µm)		ϑ (″)	
	bias	u	bias	u	bias	u
ICP	0.013	0.053	4.426	0.052	1077.830	0.585
ODF	0.012	0.140	0.002	0.086	0.359	3.130
	MAE (µm)		**RMSE (µm)**		**PV (µm)**	
	bias	u	bias	u	bias	u
ICP	14.028	0.043	17.719	0.045	70.330	0.933
ODF	0.001	0.070	0.997	0.040	5.722	0.520

As shown in Table 1, the numerical stabilities of the ICP and ODF are comparable, which is indicated by the uncertainties of the estimated parameters. The biases and the MAE, RMSE and PV values obtained using the ODF are all lower than those obtained in the ICP. This means the parameters obtained in the ODF are more accurate. Moreover, the ODF is optimal over ICP due to a fact that it not only is used for the registration of the measured cam profile, but also is employed for form error evaluation.

4. Conclusion

An approach is presented to evaluate the form deviation of the cam profile. In reconstruction of the cam template, the parameter selection affects the reconstruction error. Compared to the ICP method, the proposed approach is able to achieve more accurate rotation and position parameters. In order to further validate the proposed algorithm, more numerical experiments need to be implemented.

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