Cylinder head gasket design optimization based on high definition metrology

Yaxiang Yin\textsuperscript{1,2}, Kun Wang\textsuperscript{1,2}, Yiping Shao\textsuperscript{3}, Shichang Du\textsuperscript{1,2,4}, Lifeng Xi\textsuperscript{1,2} and Tangbin Xia\textsuperscript{1,2}

\textsuperscript{1} State Key Lab of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai, 200240, China
\textsuperscript{2} School of Mechanical Engineering, Shanghai Jiao Tong University, No. 800 Dongchuan Road, Shanghai 200240, China
\textsuperscript{3} College of Mechanical Engineering, Zhejiang University of Technology, Hangzhou, China
\textsuperscript{4} E-mail: lovbin@sjtu.edu.cn

Abstract. Traditional cylinder head gasket design is based on the assumption that the mating surfaces' form is ideal plane. However, high definition metrology (HDM) shows that the top surface of cylinder blocks and the bottom surface of cylinder heads are far from ideal plane and presents a macro form error. To compensate the macro form error of the mating surfaces, a gasket design optimization method is proposed in this paper. It mainly consists of two modules. The first module is surface alignment and gap calculation. Measured surface topography is aligned by control point registration and the control points are found by region labelling algorithm. The second module is gasket design optimization based on surface gap. A case study shows the details of the proposed gasket design optimization method.

1. Introduction

Cylinder head gasket is a crucial element for sealing in automobile engine assembly. The multi-layer steel (MLS) gasket is the most popular gasket scheme for its reliable sealing performance and rich design possibilities [1]. The most important function of the gasket is to prevent the gas in combustion chamber from leakage. The first combustion seal on the gasket is called stopper, and it is a zone at the bore opening which is thicker than the rest of the gasket. The secondary combustion seal is the full bead or embossments. Figure 1 shows the concept of stopper and full bead. Since the surface topography of the mating cylinder head and block is rough in micro view, the pressure distribution on the stopper zone is not uniformly [2]. To guarantee the sealing of combustion chamber, it is required that the weakest pressure spot in stopper zone is greater than the maximum operation pressure of the engine. So, in practice the torque of the cylinder head bolts is very high. However, high loading by bolts caused the bore distortion and reduced the life of the gasket. Thus, it is desired to achieve uniformly distributed pressure on the stopper zone.

One important reason of the non-uniformity of pressure distribution on the stopper zone is the rough topography of the mating surfaces. The contact pressure will be high if the surface gap on that spot is small and the contact pressure will be low if the surface gap on that spot is big. If the surface gap on the stopper zone is known in advance, the stopper topography could be designed to compensate the surface gap so as to achieve a relative uniform distributed pressure. However, surface gap is not
measureable directly. To solve this problem, an indirect surface gap inferring method is proposed in this paper with the aid of high definition metrology (HDM).

Figure 1. Structure of a single layer of the MLS gasket.

In recent years, precision measurement has developed rapidly. One of the noncontact measurement instrument named high definition metrology (HDM) is used to measure engineering surfaces with large size. It can generate a surface height map of millions of data points for 3D inspection of a surface [3]. The HDM instrument and an example of the engine block surface measured by HDM are shown in Figure 2. The 3D surface topography examined by HDM presents a new platform, several researches based on HDM such as 3D surface topography filtering [4-6], classification [7, 8], forecasting [9, 10] and leakage monitoring [11-13] have been explored. With the help of HDM, a surface topography alignment method is proposed to calculate the surface gap distribution.

Figure 2. Measurement by HDM.

The remainder of this paper is organized as follows: a detailed surface topography alignment method is presented in Section 2. In Section 3, a case study demonstrates the effectiveness of the surface alignment method and shows the gasket design optimization result. The last section draws the conclusions and discusses the future research.

2. Methodology

HDM is employed to measure the engineering surfaces and generate millions of points. Since the original HDM data is in a coordinates form and not exactly equidistant sampled. To extract the feature points and apply image registration algorithm to align two measured surfaces, it is necessary to convert the measurement data into a matrix form or an image. The preprocessing method developed in Reference [14] is used to transform HDM coordinates \([X, Y, Z]\) into a gray pixel \(I(m, n)\). The transformed gray image contains all the height and spatial information of the original HDM data. A binary image \(B(m, n)\) can also be generated to judge the boundaries and holes of the surfaces. Based on the matrix form of the surface topography, the workflow to align two engineering surfaces is shown in Figure 3.

Figure 3. Workflow to align two engineering surfaces.
2.1. Region labelling and feature points extraction

Labelling the feature regions (connected components) of the binary image, such as bolt holes and cylinder bores, can help to extract assembly feature points. Typical feature points include the centroids of circles or the endpoints of edges.

The basic steps to label the connected components of a binary image are as follows:
Step 1: Search for the next unlabeled position, p.
Step 2: Label all the positions in the connected component containing p by a flood-fill algorithm.
Step 3: Repeat steps 1 and 2 until all the positions are given a label number.

The labelling procedures and results are demonstrated by a simple example shown in Figure 4.

\[
\{ (m, n) \mid L(m, n) = i \}
\]

Then a coordinates set of the labelled region can be defined as

\[
\{(m, n) \mid (m, n) \in C_i \}
\]

where \(|C_i|\) represents the number of elements in set \(C_i\) and \([\cdot]\) means a rounding operation. Pairs of feature points could be extracted from the two mating surfaces according to the assembly requirements. The coordinates of feature points of \(B_1\) and \(B_2\) are denoted as \([P_1, P_2, \ldots, P_m]\) and \([Q_1, Q_2, \ldots, Q_m]\) respectively, where \(m\) is the number of feature points. Two example surfaces are generated, the labelling result and feature points are shown in Figure 5.

\[
P_j = \left[ \frac{\sum (m, n)}{|C_i|} \right], \quad (m, n) \in C_i
\]

(1)

\[\text{Figure 4. Region labelling procedures.}\]
\[\text{Figure 5. Simulated surfaces and their feature points labelling.}\]
2.2. Control points registration
Two mating surfaces can be measured and transformed to two gray images $I_1$ and $I_2$. They could be registered to the same coordinate system by an affine transformation. Setting $I_1$ as the reference image, the registration error function is defined as Equation (2).

$$ f(A, b) = \sum_{i=1}^{m} |AQ_i + b - P_i|^2 $$  

(2)

Solving the optimization problem $\min f(A, b)$ could get the affine transformation matrix $T = \begin{bmatrix} A & 0 \\ b & 1 \end{bmatrix}$. Denote the pixel coordinates of $I_2$ as $(w, z)$, and the pixel coordinates of $I_2$ after registration as $(w', z')$, then $(w', z')$ can be calculated as Equation (3).

$$ \begin{bmatrix} w' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} w \\ z \\ 1 \end{bmatrix} T $$  

(3)

After registration, the coordinates of feature points on $I_2$ and $I_1$ become the same and the two images are in a common coordinate system. Figure 6 shows an example of mating surfaces whose feature points are aligned.

![Figure 6. Example of aligned two surfaces.](image)

2.3. Surface gap calculation
For aligned surface topography $z_1$ and $z_2$, the surface gap could be determined by Equation (4).

$$ d = \max(z_1 + z_2) - (z_1 + z_2) $$  

(4)

According to Equation (4), gap image $G$ can be defined as Equation (5).

$$ G = \max(I_1 + I_2') - (I_1 + I_2') $$  

(5)

3. Engineering case study
3.1. Surface gap between the cylinder block and head
The engine block and head in this case are from an automobile company. The material of the engine block and head are Cast Iron FC250 and aluminum alloy respectively. The required flatness of the two mating surfaces are both 0.05mm. The assembled engine and two mating surfaces are shown in Figure 7. The two surfaces were measured by HDM equipment ShaPix3D® 3000 series, with a vertical resolution of 0.05 µm and lateral resolution of 150 µm respectively. Its field of view is 280 mm × 280 mm, and the maximum number of sampling points is 4 million in each view. For workpieces whose sizes exceed the field of view, the HDM could stitch multiple point clouds to generate the full view of the surfaces. After pre-processing of the measurement data, the converted gray images which represent the height map of the surfaces are shown in Figure 8.

By labelling algorithm introduced in Section 2.1, the feature points (centroids of the bores and holes) are obtained. The labelling results are shown in Figure 9. And the assembly requirements of these points are listed in Table 1.
Figure 7. The assembled engine and the two mating surfaces.

Figure 8. The height map of the mating surfaces.

Figure 9. Labelling results of the mating surfaces.

Table 1. Assembly relationship between surface features of cylinder head and block.

| surfaces | Label numbers |
|----------|---------------|
| head     | 2 28 15 17 18 16 13 11 14 12 38 37 40 39 |
| block    | 3 30 16 19 18 17 12 13 15 11 37 39 40 41 |

Using the control points registration algorithm proposed in Section 2.2, the feature points are aligned into the same coordinate system. The magenta regions in Figure 10(a) are on the surface of the block but not on the surface of the head. And the green regions indicate the opposite cases. Surface gap is calculated according to the definition in Section 2.3 and shown in Figure 10(b).
3.2. Gasket stopper height optimization

To optimize the stopper topography around the cylinder bores, the sealing gap around the bores are extracted as Figure 11 shows. The sealing gap distribution around the four bores is plotted in Figure 12. Some statistics about the four sealing gaps are calculated and listed in Table 2.

From Figure 12 and Table 2, some optimization advices could be drawn for the gasket design. The average height of the bore 2 and bore 3 are 0.01mm higher than bore1 and bore4, so it is better to design the stopper around bore2 and bore3 higher than bore1 and bore4 to achieve better load balance. Another observation is that the height range of sealing gap around bore1 and bore4 are higher than bore2 and bore3. So it is better to design the stopper topography varies in accordance with the gap height distribution rather than a constant height of all the stoppers, especially for stoppers around bore1 and bore4.
4. Conclusions
This paper presents a novel surface alignment method to calculate the surface gap distribution based on HDM. The alignment algorithm mainly consists of three steps: region labelling to find the feature points, control points registration to align these feature points, and surface gap calculation. The case of interface between cylinder block and head shows the effectiveness of the surface alignment method, and some gasket optimization advices are given to improve the sealing performance of this interface.

Acknowledgements
Financial supports from National Natural Science Foundation of China (Grant No. 51535007, 51775343, 51875359) and Ministry of Education-China Mobile Research Foundation (CMHQ-JS-201900003) are acknowledged.

References
[1] Capretta R and Ohigashi H 1995 Design methodology for automotive multi-layer steel cylinder head gaskets SAE Technical Paper 950322
[2] Kestly M, Unseld G, Weiss A and Ludwig J 2003 MLS cylinder head gasket wave stopper SAE Technical Paper 2003-01-0474
[3] Huang Z, Shih A J and Ni J 2006 Laser interferometry hologram registration for three-dimensional precision measurements Journal of Manufacturing Science and Engineering 128(4) pp. 887-896
[4] Du S C, Liu C P and Huang D L 2015 A shearlet-based separation method of 3D engineering surface using high definition metrology Precision Engineering 40 pp. 55-73
[5] Wang M, Shao Y P, Du S C and Xi L F 2015 A diffusion filter for discontinuous surface measured by high definition metrology International Journal of Precision Engineering and Manufacturing 16(10) pp. 2057-2062
[6] Shao Y, Wang K, Du S and Xi L 2018 High definition metrology enabled three dimensional discontinuous surface filtering by extended tetrolet transform Journal of Manufacturing Systems 49 pp. 75-92
[7] Du S C, Liu C P and Xi L F 2015 A selective multiclass support vector machine ensemble classifier for engineering surface classification using high definition metrology Journal of Manufacturing Science and Engineering 137 011003-1-15
[8] Du S C, Huang D L and Wang H 2015 An adaptive support vector machine-based workpiece surface classification system using high-definition metrology IEEE Transactions on Instrumentation and Measurement 64(10) pp. 2590-2604
[9] Wang M, Du S C and Xi L F 2015 Predicting machined surface topography based on high definition metrology 15th IFAC Symposium on information control problems in manufacturing INCOM pp. 1013-1017
[10] Shao Y, Du S and Xi L 2017 3D machined surface topography forecasting with space-time multioutput support vector regression using high definition metrology 37th Computers and Information in Engineering Conference Cleveland Ohio, USA, p. V001T002A069
[11] Shao Y, Yin Y, Du S, Xia T and Xi L 2018 Leakage monitoring in static sealing interface based on three dimensional surface topography indicator Journal of Manufacturing Science and Engineering 140 p. 101003
[12] Shao Y, Yin Y, Du S and Xi L 2019 A surface connectivity based approach for leakage channel prediction in static sealing interface Journal of Tribology pp. 1-32
[13] Ren J, Park C and Wang H 2018 Stochastic modeling and diagnosis of leak areas for surface assembly Journal of Manufacturing Science and Engineering 140(4)
[14] Meng W, Xi L and Du S 2014 3D surface form error evaluation using high definition metrology Precision Engineering 38(1) pp. 230-236