Study on Deformation Characteristics of Diesel Engine Cylinder Liner under Different Influencing Factors

ZHU Xinran*, CHENG Yingb*, WANG Longc
School of Mechanical Engineering, Beijing Institute of Technology, Beijing, China
*aemail: maggizhu217@126.com
bemail: chengy@bit.edu.cn

Abstract: To study the influence of different influencing factors on the cylinder liner deformation characteristics, the finite element method was used to analyze the cylinder liner deformation under the pre-tightening condition of the diesel engine block-cylinder head assembly. Fourier spectrum, coaxiality, and main thrust surface inner diameter change were selected as deformation evaluation indicators to comprehensively evaluate cylinder liner deformation. The influence laws of several typical load parameters, structural parameters, and material parameters on cylinder liner deformation have been studied and sensitivity has been used to characterize the degree of influence of influencing factors on each deformation evaluation indicator. The research results can guide the evaluation and control of cylinder liner deformation under the pre-tightening condition.

1. Introduction
As one of the key components of internal combustion engines, cylinder liners are closely related to the performance of internal combustion engines. Under the development trend of the increasing power density of diesel engines, the increase in the maximum burst pressure leads to an increased pre-tightening force of cylinder head bolts. With the increase of load acting on the cylinder liner, whole cylinder liner deformation increases.

Excessive deformation of the cylinder liner will lead to a series of failure problems, such as excessive out-of-round deformation on the cross-section, which will cause gas leakage and carbon deposition, resulting in reduced combustion efficiency, increased oil consumption, and worse emissions. Excessive longitudinal deformation of the cylinder liner will increase the gap between the piston skirt and the inner surface of the cylinder liner, poor lubrication performance, and increased friction power consumption. In severe cases, the piston movement will be blocked and the cylinder will be pulled or stuck. Therefore, it is of great significance to study the deformation characteristics of cylinder liners under the pre-tightening condition.

Many researchers have discussed the deformation of the cylinder liner and its influencing factors. Koch et al. [1] established a finite element model of an internal combustion engine and analyzed the influence of bolt engagement length, water jacket structure, and different working conditions on cylinder liner deformation. Maassen et al. [2] summarized the methods for optimizing the deformation of the cylinder liner according to the influencing factors of the cylinder liner deformation. Cao et al. [3] used the out-of-roundness as the evaluation indicator to optimize the bolt tightening torque and the diameter of the cylinder liner ring. Wu et al. [4] used the radial deformation of the cylinder liner and the Fourier deformation amplitudes as evaluation indicators and studied the influence of the local...
stiffness of the cylinder head and the structure of the cylinder liner on the deformation of the cylinder liner. Since it is difficult to measure the cylinder liner deformation under working conditions, most of the current engineering only evaluates the cylinder liner deformation under assembly conditions [5,6]. These studies have provided a lot of experience for the analysis of cylinder liner deformation. However, since it is difficult to describe the cylinder liner deformation with a single evaluation indicator, a comprehensive evaluation of the cylinder liner deformation is lacking.

In this study, to comprehensively evaluate the deformation characteristics of the cylinder liner, the Fourier spectrum, the change in the inner diameter of the main thrust surface, and the coaxiality were selected as the cylinder liner deformation evaluation indicators. Based on one 6V type diesel engine, a finite element model of the block-cylinder head assembly was built, and the influence laws of cylinder head bolt pre-tightening force, cylinder head material, cylinder liner material, cylinder liner shoulder inclination, and shoulder height on deformation characteristics were summarized. The sensitivity was used to characterize the influence degree of each influencing factor on the evaluation indicators of cylinder liner deformation, to reflect the deformation law of cylinder liner in the cross-section, longitudinal section, and the whole, thus providing a theoretical basis for the evaluation and control of cylinder liner deformation.

2. Finite element model establishment and verification

2.1. Finite element model
Based on the 6V type diesel engine, a simplified geometric model of each component of the middle cylinder was established. The geometric structure of unimportant parts was simplified to reduce the number of grids, improve the quality of the grids, and reduce the scale of calculations. Besides, mesh refinement was carried out in areas with larger deformations and contact areas. The cylinder liner, cylinder head gasket, cylinder head bolts, and cylinder liner support ring were respectively divided into hexahedral meshes, and the cylinder head and block were divided into tetrahedral meshes. The assembly model and the mesh model of the cylinder liner are shown in Figure 1.

Figure 1. Model of the block-cylinder head assembly and the mesh model of the cylinder liner

2.2. Boundary conditions
The cylinder liner support ring and cylinder block, bolts, and cylinder head, bolts, and cylinder block were set as binding constraints since this study focused on the cylinder liner. Moreover, the cylinder liner and support ring, cylinder liner and block, cylinder liner and cylinder head gasket, and cylinder head gasket and cylinder head were arranged in small sliding contact. The coefficient of friction between the contact pairs was set to 0.15.

Symmetrical displacement constraints were set on the split surface of the cylinder block model, normal displacement constraints were set on the contact surface between the bottom of the cylinder block and the oil pan, and full constraints were set on the hole of the main bearing seat.
The cylinder head is fastened to the cylinder block by four pre-tightening bolts. The pre-tightening force in Abaqus adopted the Bolt Load method, and the standard pre-tightening force was set to 130KN.

2.3. Model verification
By carrying out the stress and strain test of the diesel engine cylinder head-block assembly, the simulation analysis results of the finite element model were compared with the test results to verify the rationality of the model.

According to the results of the finite element simulation analysis under the pre-tightening condition, the high-stress areas of the cylinder head, block, and cylinder liner were selected as the measuring points of the strain gauges. Figure 2 shows the comparison between experimental measurement results and simulation results. Measuring points 1 and 2 are located on the top plane of the cylinder block diaphragm, points 3~6 are located at the cross-section of the cylinder liner 10mm away from the top plane, and points 7~9 are located near the bolt holes on the side plate and the top plate of the cylinder head. The relative error between the calculation result and the test result of the measured point stress value was within 10%, indicating that the simulation model was established relatively accurately, and the following study on the cylinder head-block assembly can be continued.

3. Comprehensive analysis of cylinder liner deformation under different influencing factors
To study the deformation characteristics of cylinder liners under different load parameters, structural parameters, and material parameters, the pre-tightening force of cylinder head bolts, cylinder liner shoulder height, shoulder inclination, cylinder head material, and cylinder liner material were selected as influencing factors.

Evaluation indicators of cylinder liner deformation can be divided into three types: cross-section type, longitudinal section type, and integral type. Among them, the degree of out-of-roundness and Fourier spectrum are cross-sectional deformation evaluation indicators, which can describe the radial deformation in the cross-section of the cylinder liner, and are used to study the air leakage caused by the out-of-round cylinder liner. The inner diameter change of the main thrust surface and the vertical surface of the main thrust surface is the longitudinal section deformation evaluation indicator, which can describe the longitudinal section deformation of the cylinder liner, and is used to analyze the passage of the piston after the cylinder liner is deformed to avoid cylinder pulling or jamming. Axial deflection and coaxiality are the overall deformation evaluation indicators, which can describe the overall movement of the cylinder liner and are used to separate the overall movement in the deformation data [7]. It is difficult to describe the deformation characteristics of cylinder liners with a single evaluation indicator. Therefore, according to the classification, the Fourier spectrum, the change
in the inner diameter of the main thrust surface, and the coaxiality were selected as the evaluation indicators for the cylinder liner deformation.

The deformation data of the inner surface of the cylinder liner was extracted, and three deformation evaluation indexes under different influencing factors were calculated using Matlab programming.

3.1. The influence of bolt pre-tightening force on cylinder liner deformation

According to the pre-tightening force value range, took the pre-tightening force as 120, 125, 130, 135, and 140KN. To study the deformation law of the cross-section, the node data on section 10mm, 70mm, 128mm away from the top plane of the cylinder liner were selected respectively, and the magnitude of the 0 ~ 6th orders Fourier deformation was calculated. Figure 3 shows the Fourier deformation amplitudes on each section of the cylinder liner with different cylinder head bolt pre-tightening forces. In addition to the 0-order shrinkage deformation at the top and the 1st-order global center offset deformation, the inner surface deformation of the cylinder liner is mainly manifested as 2nd-order elliptical deformation and 4th-order deformation. Because the cylinder body is made of aluminum alloy, the overall rigidity is small, and the rigidity of the diaphragm between the two cylinders is small. Therefore, when the bolt pre-tightening force is applied, the left and right sides of the cylinder liner near the diaphragm of the cylinder block have a greater amount of deformation, resulting in elliptical deformation, and at the same time, the four-cylinder head bolt positions also produce corresponding deformations, that is, 4th-order deformation. The 0-order shrinkage deformation at the top section of the cylinder liner increases significantly with the increase of the pre-tightening force. The 2nd-order deformation of the upper section of the cylinder liner is larger, and the bottom section has a smaller deformation, and the increase of the pre-tightening force increases the deformation amplitude. The 4th-order deformation of the middle and upper part of the cylinder liner is relatively large, and the 4th-order deformation at the bottom is zero, and the deformation amplitude of the top section increases slightly with the increase of the pre-tightening force, while the deformation amplitude of the middle and lower part of the cylinder liner is unchanged. The deformation amplitude changes of other orders are relatively small.
Figure 3. Fourier amplitude of each order under different pre-tightening force on each section

Figure 4 shows the cylinder liner coaxiality and the change of the inner diameter of the main thrust surface under different cylinder head bolt pre-tightening forces. It can be seen that the coaxiality and the change of the inner diameter of the main thrust surface both increase with the increase of the pre-tightening force, indicating that the increase of the pre-tightening force causes the overall movement of the cylinder liner and the deformation on the longitudinal section to become larger.

3.2. The influence of structural parameters on cylinder liner deformation

3.2.1. The influence of the cylinder liner shoulder height on cylinder liner deformation.

The shoulder heights were taken at equal intervals of 6, 6.5, 7, 7.5, and 8mm, and the data of the inner surface of the cylinder liner was calculated. Figure 5 shows the Fourier amplitudes on each section of the cylinder liner under different heights of the cylinder liner shoulder. As shown in the figure, the influence of the height of the shoulder on the deformation amplitude is relatively small, and the 2nd-order elliptical deformation on the lower section of the cylinder liner slightly increases when the height of the shoulder increases.
Figure 5. Fourier amplitude of each order under different heights of cylinder liner shoulders on each section.

Figure 6 shows the cylinder liner coaxiality and the change in the inner diameter of the main thrust surface when the height of the cylinder liner's shoulder is different. As the height of the shoulder increases, the coaxiality of the cylinder liner changes very little and slightly increases, while the amount of change in the inner diameter gradually decreases.

Figure 6. Coaxiality and change of inner diameter of main thrust surface under different heights of cylinder liner shoulders

3.2.2. The influence of the cylinder liner shoulder inclination on cylinder liner deformation.

The calculation was carried out by taking the data of the inner surface of the cylinder liner when the shoulder inclination angle was 0°, 0.2°, 0.4°, 0.6°, and 0.8°. Figure 7 shows the Fourier amplitudes on each section of the cylinder liner with different shoulder inclination angles. It can be seen from the
figure that the 0-order shrinkage deformation at the top section of the cylinder liner increases with the increase of the shoulder inclination, while the 2nd-order elliptical deformation at the middle and lower sections decreases, and the amplitude of other orders changes relatively small.

![Figure 7. Fourier amplitude of each order under different inclination angles of cylinder liner shoulders on each section](image)

As shown in Figure 8, as the shoulder inclination becomes larger, the cylinder liner's coaxiality changes very little, and the change in the inner diameter of the main thrust surface first decreases and then increases, and the minimum value is obtained at 0.2°.

![Figure 8. Coaxiality and change of inner diameter of main thrust surface](image)
3.3. The influence of material parameters on cylinder liner deformation

Material parameter changes mainly include the influence of changes in the elastic modulus $E$ and Poisson's ratio $\nu$ of each component on the deformation of the cylinder liner. However, because the variable range of Poisson's ratio is very small, only the effect of changes in the elastic modulus of components on the deformation of the cylinder liner was studied. To show the changes in the stiffness matching of the parts caused by the changes in material parameters, the elastic modulus $E_b$ of the cylinder block was selected as the benchmark, and $a=E_b/E_\theta$ and $b=E_\theta/E_b$ were used to denote the relative elastic modulus of the cylinder head and the block and the relative elastic modulus of the cylinder liner and the block. The material parameters of other parts remained unchanged. Since the load parameters and structural parameters of the model are unchanged, it can reflect the influence of the change of the equivalent stiffness ratio between the cylinder head, cylinder liner, and block on the cylinder liner deformation to a certain extent.

3.3.1. The influence of the cylinder head material on cylinder liner deformation.

According to the relative elastic modulus of the original material of the cylinder head, the data of the inner surface of the cylinder liner when $a$ is 1.4, 1.6, 1.8, 2.0, and 2.2 were taken for the calculation. Figure 9 shows the Fourier amplitudes on each section of the cylinder liner under different relative elastic moduli of the cylinder head. The second-order elliptical deformation changes at each section of the cylinder liner are obvious and decrease with the increase of the relative elastic modulus of the cylinder head. It shows that to reduce the out-of-round deformation of the cross-section, the design stiffness of the cylinder head should be increased as much as possible when conditions permit.

![Fourier amplitude of each order under different relative elastic moduli of the cylinder head on each section](image)

(c) 128mm section

Figure 9. Fourier amplitude of each order under different relative elastic moduli of the cylinder head on each section

Figure 10 shows the cylinder liner coaxiality and the change in the inner diameter of the main thrust surface when the relative elastic modulus of the cylinder head is different. With the increase of $a$,
the coaxiality of the cylinder liner first decreases and then increases, but the overall change is smaller, and the amount of change in the inner diameter decreases. It shows that the overall movement of the cylinder liner is the smallest when \( a \) is about 1.8, and if conditions permit, increasing the design stiffness of the cylinder head can reduce the deformation of the longitudinal section of the cylinder liner.

![Graphs showing coaxiality and change of inner diameter of main thrust surface under different relative elastic moduli of the cylinder head](image)

(a) Coaxiality  
(b) Change of inner diameter of main thrust surface

Figure 10. Coaxiality and change of inner diameter of main thrust surface under different relative elastic moduli of the cylinder head

3.3.2. The influence of the cylinder liner material on cylinder liner deformation.

According to the relative elastic modulus of the original material of the cylinder liner, \( b \) was taken as 2.2, 2.4, 2.6, 2.8, and 3.0 respectively. Figure 11 shows the Fourier amplitudes on each section of the cylinder liner under different relative elastic moduli of the cylinder liner. It can be seen from the figure that the 0-order shrinkage deformation at the top section of the cylinder liner decreases with the increase of the relative elastic modulus of the cylinder liner, and the amplitude changes of other orders are relatively small.

![Graphs showing Fourier amplitudes on sections of cylinder liner under different material elastic moduli](image)

(a) 10mm section  
(b) 70mm section

Figure 11. Fourier amplitudes on sections of cylinder liner under different material elastic moduli.
Figure 11. Fourier amplitude of each order under different relative elastic moduli of the cylinder liner on each section

The cylinder liner coaxiality and the change in the inner diameter of the main thrust surface under different relative elastic moduli of the cylinder liner are presented in Figure 12. The increase of \( b \) causes the coaxiality to decrease first and then increase, but the overall change is small, and the amount of change in the inner diameter decreases. Therefore, when \( b \) is set to 2.4, the overall movement of the cylinder liner is the smallest, and the greater the design stiffness of the cylinder liner, the smaller the deformation on the longitudinal section of the cylinder liner.

4. Sensitivity comparative analysis

To analyze the degree of influence of each influencing factor on the evaluation indicator of cylinder liner deformation, sensitivity was used for characterization. Sensitivity was defined as the ratio of the change degree of evaluation indicators to the change degree of influencing factor parameters:

\[
\text{sensi} = \frac{(\text{indicator}_i - \text{indicator})/\text{indicator}}{(\text{parameter}_i - \text{parameter})/\text{parameter}}
\]  

(1)

As mentioned above, the influencing factor parameters have 4 values each with a fixed step length, and the average value of these 4 corresponding sensitivities is used as the final sensitivity. In this way, the sensitivity of each cylinder liner deformation evaluation indicator to each influencing factor was calculated. The evaluation indicators include 2nd and 4th order Fourier amplitude, coaxiality, and inner diameter change of the main thrust surface, as shown in Figure 13, where x1, x2, x3, x4, and x5
respectively represent the cylinder head bolt pre-tightening force, cylinder liner shoulder inclination angle, shoulder height, cylinder head material, and cylinder liner material parameters.

![Figure 13. Sensitivity of evaluation indicators to various influencing factors](image)

5. Conclusions

(1) In the pre-tightening condition, the inner surface deformation of the cylinder liner is mainly manifested as the 2nd-order elliptical deformation and the 4th-order deformation caused by the bolt pre-tightening, in addition to the top plane shrinkage deformation and the overall center offset deformation.

(2) According to several typical load parameters, structural parameters, and material parameters, different influencing factors have different effects on cylinder liner deformation and evaluation indicators. Among them, cylinder head bolt pre-tightening force has the greatest impact on cylinder liner deformation. However, the change of the same influencing factor has different influence rules on different evaluation indicators, indicating that it is necessary to use different types of evaluation indicators for the comprehensive evaluation of cylinder liner deformation.

(3) The 2nd-order deformation on the cross-section of the cylinder liner is greatly affected by the pre-tightening force and the material of the cylinder head; while the 4th-order deformation is greatly affected by the pre-tightening force, the cylinder head material, and the cylinder liner material. The coaxiality is greatly affected by the pre-tightening force. The change in the inner diameter of the main
thrust surface is more sensitive to changes in the pre-tightening force, cylinder head material, cylinder liner material, and shoulder height (sorted in descending order of influence). This study can guide the evaluation and control of cylinder liner deformation under the pre-tightening condition.

References
[1] Koch, F., Decker, P., Robert Gülpen, Quadflieg, F. J., Loeprecht, M. (1998). Cylinder Liner Deformation Analysis - Measurements and Calculations. International Congress & Exposition.
[2] Maassen, F., Koch, F., Schwaderlapp, M., Ortjohann, T., Jürgen Dohmen. (2001). Analytical and Empirical Methods for Optimization of Cylinder Liner Bore Distortion. IEEE Eleventh International Symposium on Autonomous Decentralized Systems.
[3] Cao M., Yang Z.. (2000). Finite element calculation and analysis of cylinder liner deformation of 6110 diesel engine. Journal of Jiangsu University of Science and Technology (Natural Science Edition), 21(003), 33-37.
[4] Wu B., Xu G., Hu D., Wang X.. (2013). Analysis of influencing factors of deformation of internal combustion engine wet cylinder set. Small internal combustion engine and motorcycle, 02(2), 21-21.
[5] Bi Y., Xiang R., Zhang N., Lei J., Shen L.. (2016). Analysis of the influence of different mechanical loads on cylinder liner out-of-round. Journal of Kunming University of Science and Technology (Natural Science Edition), 041(005), 65-72.
[6] Xu Y., Wen Z., Bi Y., Lei J., Shen L.. (2016). Research on the effect of cylinder liner thickness on cylinder liner deformation of diesel engines. Internal Combustion Engines and Accessories, 000(001), 1-6.
[7] Li C.. (2009). Research on Deformation and Dynamic Characteristics of Internal Combustion Engine Cylinder Liner. Beijing Institute of Technology, Beijing.