Research on the Finite Element Analysis of the Sealing Property of the Piston Used in Automobile Teaching

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Abstract. In recent years, the continuous development of the national economy has promoted the popularity of automobiles. In the course of automobile teaching, the tightness of the internal combustion engine and its piston in the teaching vehicle is an important factor determining the safety performance of the vehicle. The traditional method for analyzing the tightness of pistons for teaching often causes corresponding adverse effects due to the poor accuracy of the results. Therefore, this study designs a finite element analysis method for the sealing of pistons for automotive teaching. First analyze the shape and material characteristics of the piston for automotive teaching, and then build a finite element model of the piston for automotive teaching to complete the processing of piston stress load. Based on this, the research on piston sealing performance is realized according to the coupling analysis process. The experimental results show that the accuracy of the method is better than that of the traditional method, and the analysis process is less time-consuming, which fully proves the effectiveness of the method.

Keywords: Finite element analysis · Piston · Tightness · Coupling analysis · Finite element model

1 Introduction

With the continuous popularization of private cars, more and more people need to receive car driving instruction. In teaching vehicles, the tightness of the internal combustion engine is one of the important factors determining its safety performance, and the piston in the internal combustion engine is one of the decisive factors for the sealing performance of the internal combustion engine [1, 2]. As a key component of internal combustion engine, the sealing property of piston is directly related to the working reliability and durability of high-speed internal combustion engine, and also directly affects the emission performance of internal combustion engine. The top surface of the piston is subject to the transient high temperature of the gas, which makes the top of the piston and even the entire piston very hot, and the temperature field is very unevenly distributed.
The temperature gradients in various parts are different, causing the piston to deform thermally. The surface cracked, causing the gap between the piston and the cylinder liner to be damaged, and even the phenomenon of the piston pulling the cylinder and locking. Therefore, it is necessary to carry out research and analysis on the tightness of the piston, understand the sealing state and comprehensive stress distribution of the piston, and then improve and optimize the piston, improve the sealing ability of the piston, improve its thermal stress distribution, and improve the work of the piston of the special vehicle for automotive teaching. Reliability and improved emissions are important [3].

In the traditional analysis process, the piston is generally regarded as a whole, and the analysis perspective is relatively macro, resulting in the problem of poor accuracy of the analysis results. Therefore, in this study, the finite element method is used to optimize the sealing analysis process. The finite element method is a very effective numerical calculation method, which can calculate the deformation, stress and dynamic characteristics of various structures with irregular geometry, complex load and support. The finite element analysis of the sealing of the piston for automobile teaching can improve the driving safety of the teaching car, and at the same time, it also further protects the personal safety of the coach and the students.

2 Method Design

In the traditional process of analyzing the sealing property of the piston used in automobile teaching, the piston will be generally analyzed as a whole, resulting in the low accuracy of the final analysis results. In order to solve this problem, based on the traditional analysis method, this study uses the finite element analysis process to design the piston sealing finite element analysis method for automobile teaching. The design process is as follows (Fig. 1).
Because the construction and analysis of the finite element model are involved in this design process, in order to ensure the accuracy of the analysis results, it is necessary to pay attention to the size of the segmentation unit when unfolding the segmentation to avoid affecting the accuracy of the analysis results.

2.1 Analysis of the Shape and Material Characteristics of Pistons Used in Automobile Teaching

In order to improve the reliability of the analysis results, before constructing the finite element model, the shape and material characteristics of the piston for automobile teaching should be studied. In general, the shape of the internal combustion engine piston of the teaching automobile is a circular piston with a necked mouth, and its material is ZL109 g silicon aluminum alloy \([4, 5]\). At room temperature, the elastic modulus is \(E = 7000 \text{ MPa}\), Poisson’s ratio is \(\mu = 0.25\), density is \(\rho = 2.5 \times 10^3 \text{ kg/m}^3\), thermal
conductivity is $\lambda = 125 \text{ W/(m.k)}$, and at 10 °C–200 °C, the linear expansion coefficient of the material is $\chi = 20.95 \times 10^{-6}/\text{°C}$, the tensile strength of the material is $\delta_a = 265.5 \text{ MPa}$, and the compressive strength is $\delta_b = 270.5 \text{ MPa}$. In addition to the above, other performance parameters of the piston shall be considered in the actual analysis process, as shown in Table 1.

Table 1. Other parameters of piston for automotive teaching

| Parameter type          | Parameter serial number | Parameter contents                                      |
|------------------------|-------------------------|--------------------------------------------------------|
| Basic parameters       | 1                       | Piston skirt diameter                                   |
|                        | 2                       | Piston top diameter                                     |
|                        | 3                       | Piston skirt length                                     |
| Internal part parameters| 4                       | Piston height                                           |
|                        | 5                       | Pin hole diameter                                       |
|                        | 6                       | Height from center of pin hole to top surface           |

Generally speaking, the working environment in which pistons are located is relatively harsh. Therefore, in order to ensure the safety and stability of internal combustion engines used in automobile teaching, the performance requirements of piston materials are high. When selecting piston materials, the following conditions need to be met: small density, small thermal expansion coefficient, good wear resistance, mechanical properties, thermal conductivity, and good processability.

The physical diagram of the piston for automobile teaching is shown in Fig. 2.
Through the research of the above piston material characteristics, we can fundamentally improve the design accuracy of the finite element model of automobile piston for teaching. At the same time, the rationality of the finite element analysis process can be improved by studying the material properties.

2.2 Constructing Finite Element Model of Piston for Automobile Teaching

The above analysis is used as the basis for constructing the finite element model, and the computer is used to simulate and analyze the piston.

In recent years, in addition to the continuous development of computer technology and the widespread use of high-performance computers, some large-scale modeling software and computing software have also been improved in practice and matured. In the finite element analysis software, ANSYS/LS-DYNA has been widely used for its superior economic applicability [6]. ANSYS integrates CAD, CAE and CAM technology, which can meet the user’s requirements in the whole process from design, calculation to manufacturing. For this reason, in the research of finite element analysis of teaching piston, the three-dimensional modeling and finite element mesh generation of piston are carried out by ANSYS software.

Considering that the piston is a complex three-dimensional component, the combustion chamber offset at the top, the existence of the piston pin seat and the shape of the internal cavity are extremely complicated, so that the entire piston does not have axisymmetric properties. Therefore, when three-dimensional modeling of the piston, in order to more realistically and objectively reflect the actual working condition of the piston, the root system of the piston was fired as a whole, and the three-dimensional modeling of the piston was strictly performed in accordance with the dimensions of the drawing. Considering comprehensively the influence of calculation accuracy and the
influence of calculation scale on the piston, the model needs to be simplified, and the piston solid model diagram is shown in Fig. 3.

![Fig. 3. Construction results of finite element model for teaching piston](image)

When the 3D solid model of piston is meshed by finite element method, the tetrahedral element in t-deas software is used to realize the automatic meshing of solid model. For the key parts such as combustion chamber, piston pin seat hole and piston ring groove, the t-deas software is used to select the size and shape of the part at will, so as to better express the surface boundary of the piston [7]. Considering both the number of units and the calculation time, this study uses regular meshing for the main body of the piston, and free meshing for the rest. The number of elements and nodes of the piston mesh can meet the requirements of engineering accuracy without consuming more calculator time. Using the designed model as the basic model of the analysis process, the sealing analysis is completed after the finite element is divided.

2.3 Stress Load Treatment of Piston

The piston finite element model obtained by the above design is segmented. Analyzing the working process of the piston, it can be known that when the pressure of the gas of the internal combustion engine of the automobile reaches the maximum, the piston is subjected to the most severe stress and deformation under the condition of stable speed. Therefore, the piston should be selected as the analysis condition at the rated power and the highest burst pressure.

Assume the maximum burst pressure $P_z = 10.2516$ MPa that the piston can withstand. The explosive pressure acts on the top surface of the piston, the surface of the combustion chamber, the shore of the firepower, and the ring groove. The pressure inside
the first ring groove is 0.70 Pz. The pressure between the first ring and the second ring is 0.30 Pz; the pressure inside the second ring is 0.30 Pz.

Generally, the inertia force of piston is reciprocating inertia force. The direction of reciprocating inertia force is opposite to that of piston acceleration, and the action line is parallel to the cylinder center line. Omitting the slight deviation between the reciprocating mass center and the cylinder center line, we can think that the action line of the reciprocating inertia force coincides with the cylinder center line. The reciprocating inertia force can be determined by Eq. (1):

\[ A_i = -m_i v \] (1)

In the formula: \( m_i \) represents the mass of the piston, \( v \) represents the acceleration of the piston, and the unit is \( \text{m/s}^2 \). The comprehensive stress of the piston can be obtained through the calculation of the above formula.

In the solution of nonlinear finite element problems, the stress-strain relationship is generally described by the strain energy function. In the analysis of piston performance, the most widely used function is Mooney Rivlin function, and the strain potential energy can be expressed as shown in formula (2):

\[ Q = C_{10}(P_1 - 3) + C_{01}(P_2 - 3) \] (2)

In the formula: Set the mechanical property constants as \( C_{10} \) and \( C_{01} \), and set \( P_1 \) and \( P_2 \) as the strain invariants of the piston. The mechanical constants \( C_{10} \) and \( C_{01} \) of the piston can be determined by unidirectional tensile and compression tests. However, due to cost and test complexity in practice, the values of \( C_{01} \) and \( C_{01} \) are often determined by the comprehensive material properties of the piston, which can be expressed by formula (3):

\[ \log \left[ 6C_{10}(1 + \frac{C_{01}}{C_{10}}) \right] = 0.0158O - 0.524 \] (3)

In the formula: \( O \) represents the hardness of the piston material. Therefore, as long as the hardness value of the piston and the ratio of \( C_{10} \) and \( C_{01} \) are determined, the values of \( C_{10} \) and \( C_{01} \) can be determined. In general, when \( C_{10}/C_{01} \) is 0.30, the analysis result is the most reasonable.

In addition, there is an incompressible constant \( g \) in the calculation process, and its size represents the compressibility of the material. If the material is completely incompressible, then \( g = 0 \). For piston materials, there are:

\[ g = \frac{(1 - 2\delta)}{C_{10} + C_{01}} \] (4)

In the formula, \( \delta \) represents the comprehensive hardness of the piston material [8]. Through the above formula, the comprehensive stress inside the piston and the hardness characteristics of the piston are obtained, so as to facilitate the analysis of the sealing performance of the piston.
2.4 Coupling Analysis of Piston Sealing

Through the research in the above part, the construction of the finite element model of the piston is completed. In this section, the sealing performance of the piston will be analyzed. In order to ensure the validity of the analysis results, the set analysis calculation process is shown in Fig. 4.

![Fig. 4. Schematic diagram of piston sealing coupling analysis process](image)

Piston tightness analysis is performed according to the analysis process shown in Fig. 4. In this study, the calculation is only performed on the calculation part after the finite element analysis method is referenced. The specific calculation part is as follows:

Generally speaking, the reaction force of the piston pin seat acts on the contact surface between the piston pin and the inner circle of the pin hole. According to the prior knowledge, the force is distributed according to the cosine law within the 90° angle above the ring direction, and approximately according to the triangle along the axial direction. The pressure distribution curve is:

\[
W = 4 \int_{0}^{R} \int_{0}^{45} W (R - X) \cos(1.5\alpha) d\alpha dX
\]  

(5)

In the formula: \( R \) represents the length of the contact surface between the piston pin and the pin seat hole, \( X \) represents the radius of the pin seat circular hole \([9, 10]\), \( W \) represents
the combined reaction force acting on the piston pin seat, and the upper surface of the piston pin seat hole is 120°. The distributed load at any point \(a\) in the angular range is:

\[
w = w_a(R - x) \cos(60 - 1.5\alpha)
\]  

(6)

Using the above formula, the distributed load at one point of the piston is obtained. According to the calculation results of distributed load, the movement range of piston is calculated. Set the operating speed of the piston as \(y\), and calculate the range of motion as follows:

\[
t = \frac{2}{3}t_i = \frac{2}{3} \sqrt{\frac{2\mu y}{(\frac{dx}{ds})_i}}
\]  

(7)

In the formula, \((\frac{dx}{ds})_i\) represents the drunk gradient force acceptable to the piston. When the movement mode of the piston is uniform, its moving space is half of the range of the above set moving space, then there is the following formula:

\[
t = \frac{1}{2}t^y_i = \frac{1}{3}t_i = \frac{1}{3} \sqrt{\frac{2\mu y}{(\frac{dx}{ds})_i}}
\]  

(8)

Combining the above formulas, the leakage of the piston is as follows:

\[
\frac{1}{3} \pi dy \left(\sqrt{\frac{2\mu y_0}{(\frac{dx}{ds})_i}} - \sqrt{\frac{2\mu y_1}{(\frac{dx}{ds})_i}}\right)
\]  

(9)

In the formula, \(d\) represents the movement height of the piston.

Through the above results, we can know the leakage of the piston, thus reflecting the sealing performance of the piston. So far, the design of the finite element analysis method of piston sealing for automobile teaching has been completed.

3 Simulation Test Experiment and Result Analysis

In order to verify the feasibility of the finite element analysis method of piston sealing used in automobile teaching, the experimental test of the method is completed in the form of simulation experiment analysis, and the corresponding experimental results are analyzed and conclusions are drawn.

3.1 Experimental Environment Setup

In this experiment, the traditional car engine piston airtightness analysis method and the method in this paper were used to analyze the pre-prepared pistons for car teaching before the experiment, and compare the accuracy of the analysis results of different methods.

To ensure the validity of the experiment, the corresponding experimental environment is set up as follows (Fig. 5):
This experiment was completed on the Visual Studio platform. The experimental environment was an 8-core i7-5960X, a CUP of 4.0 GHz, and the simulation operating system was Matlab R2017. The finite element design software and three-dimensional simulation software are installed in the computer, and the software is used to assist the traditional method and the method of this article to complete the analysis of the experimental sample piston, and to compare the analysis results of different methods.

3.2 Experimental Samples

Based on the design of the experimental environment, in order to improve the reliability and validity of the experimental results, the experimental sample piston parameters are set as shown in Table 2.

| Parameter number | Content                              | Set value               |
|------------------|--------------------------------------|-------------------------|
| 1                | Piston material                      | Eutectic silicon aluminum alloy |
| 2                | Eutectic silicon aluminum alloy      | 0.5                     |
| 3                | Modulus of elasticity of piston      | 70 GPa                  |
| 4                | Material density                     | 3000 kg/m$^3$           |
| 5                | Thermal conductivity                 | 145.50 W/m$^*$$^k$      |
| 6                | Coefficient of thermal expansion     | 21.0*10$^{-6}$/°C       |
| 7                | Piston quality                       | 0.300 kg                |
| 8                | Piston pin mass                      | 0.150 kg                |
Set the number of experiments as 100, use the sample parameters shown in Table 2 to design the corresponding test sample piston, and use the method in this paper and the traditional analysis method to analyze it, and compare the differences between the two different methods according to the accuracy of the analysis results.

3.3 Analysis of Results

Using the above-mentioned experimental environment, analyze the piston tightness in the automobile teaching vehicle by different methods, and complete the comparison of the analysis accuracy between the traditional method and the method in this paper. The specific experimental results are shown in Table 3.

| Number of experiments | The traditional method analyzes the accuracy/% | The analytical precision of the method in this paper/% |
|-----------------------|---------------------------------------------|--------------------------------------------------|
| 10                    | 93.56                                       | 98.25                                           |
| 20                    | 96.21                                       | 96.30                                           |
| 30                    | 94.35                                       | 98.45                                           |
| 40                    | 96.26                                       | 96.54                                           |
| 50                    | 95.57                                       | 96.24                                           |
| 60                    | 95.24                                       | 97.56                                           |
| 70                    | 97.21                                       | 98.21                                           |
| 80                    | 97.20                                       | 98.01                                           |
| 90                    | 92.50                                       | 98.98                                           |
| 100                   | 90.35                                       | 98.67                                           |

By comparing the experimental results shown in Table 3, it can be known that with the continuous increase of the number of experiments, the accuracy of the results of the analysis of the piston tightness of automotive teaching vehicles by different methods is constantly changing, and the analysis accuracy of traditional methods fluctuates greatly. The analysis accuracy of the method in this paper is relatively small. It can be seen from the horizontal comparison that the analysis accuracy of the method in this paper is always higher than the traditional method. From this, it can be shown that the method of this paper has a better analysis performance of piston sealing in automobile teaching vehicles, and the analysis ability is obviously better than the traditional method.

On this basis, in order to further verify the application advantages of finite element method of piston sealing in automobile teaching, the analysis process time is taken as the experimental index, and the performance of the method in this paper and the traditional method in the analysis process time is compared, so as to judge the work efficiency of different methods.

The experimental results are shown in Fig. 6.
According to Fig. 6, although the number of experiments keeps increasing, the analysis process of the method in this paper is always less time-consuming than that of the traditional method. The minimum analysis process only takes 1.3 min, while the analysis process of the traditional method always takes more than 2 min. It can be seen that the finite element method of piston sealing designed in this paper is more efficient.

4 Concluding Remarks

In this study, ANSYS software is used to analyze the sealing performance of the piston used in automobile teaching, and the following conclusions are drawn:

When using the 3D drawing software Pro/E to establish the geometric model required for finite element analysis, the requirements of the finite element analysis method for the geometric model must be carefully considered. Some subtle structures that do not affect the analysis results should be ignored. Difficulties in meshing and calculation.

It is very important for the safety of teaching vehicles that the sealing of piston used in automobile teaching. Therefore, in the future production design, the sealing of piston should be effectively increased.

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