STUDY ON THE OPTIMAL DESIGN OF CYLINDER AND CYLINDER HEAD BY PARAMETRIC STRUCTURE CHARACTERIZATION

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Abstract

The engine cylinder head is one of the most critical components in an automotive power train system. Yet, it has the most complicated mechanical structure coupled with a sophisticated combustion process. This study attempts to develop a concrete and practical procedure for the optimal design of the engine cylinder head. First, a simplified topological model composed of beam, shell and membrane elements is developed to simulate the real cylinder head. With this model, the finite element method can be easily and economically employed to study the load-bearing mechanism of the cylinder head under actual engine operation conditions. After characterizing the stress/strain behavior of all the key components through parametric analysis, a new optimization criterion is developed based on Lagrange conditions. This criterion provides an opportunity to represent the ideal 'balanced point' among the main design parameters of the cylinder head in terms of weight distribution of the key components. Finally, the optimization of the cylinder head structure is implemented successfully based on these findings. Compared to the optimization results from commercial software, the proposed approach is able to produce a much better solution in respect to both the convergence speed and the final value of the objective function.

***Keywords**: Engine; Cylinder head; Optimal design; Topological model; Parametric structure characterization; Weight distribution criterion*

1. Introduction

In an automotive powertrain system, one of the most critical components is the cylinder head, which possesses the complicated mechanical structure coupled with a sophisticated combustion process. With the ever-increasing demand for higher engine power, the requirement for the cylinder head's loadbearing capacity is also increasing. In addition, lightweight design is also being pursued for the cylinder head, which is important for better fuel economy and vehicle safety [1, 2]. Obviously, higher load-bearing capacity and lighter weight are two conflicting goals. Therefore, realization of an ideal balanced design among the key components of the cylinder head is essential to resolve the above conflict. Traditionally, optimization of engine components such as the cylinder head was based on constructing a detailed FE model and carrying out a series of different numerical simulations. A pioneering computational work dealing with the prediction of a distorted cylinder head was performed by Chyuan [3]. Lee et al. [4] further complemented the full threedimensional FE model, and applied the contact theory to evaluate the sealing efficiency of a 2.0 L cylinder head. Later, by integrating the finite element method (FEM) and computational fluid dynamics (CFD), Shojaefard et al. [5] explored a general methodology to simulate the interactions between structural mechanics, heat transfer, and fluid coolant within the cylinder head. Other analytical and empirical contributions for the evaluation of the cylinder head structure are available in the literature [6-10]. However, the traditional approach is a computationally intensive task and it is difficult to build an effective model with precise boundary conditions during the early stages of the design. Another problem is that although constructing and calculating the detailed FE model can provide accurate simulation results, no detailed information about the load-bearing mechanism is available, and one cannot determine why the design does or does not work. To get a deep insight on the structural characteristics of the cylinder head, simple and practical FE models are still lacking and need to be explored. As a different approach, parametric analysis is very useful to evaluate the component's structural integrity. Wang et al. [11] proposed a regression-based scheme to analyze the statis-tical nature of the main parameters of the cylinder head. In another study, Zhang et al. [12] presented a detailed parametric investigation on the quantitative relationship between design parameters and structural responses. In this work, a hypothesis that there exists an ideal 'matching point' among the key components of the cylinder head was finally verified. However, a systematic approach focusing on the mathematical nature of this special 'matching point' was not given, though the 'matching point' may be utilized to get a better understanding for the optimal design of the cylinder head. To the best of the author's knowledge, this paper may be considered as an initial attempt for structure characterization and optimization of the engine cylinder head.

2. Optimal design procedure for engine cylinder head

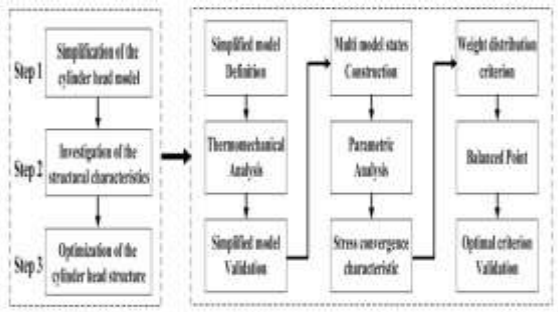
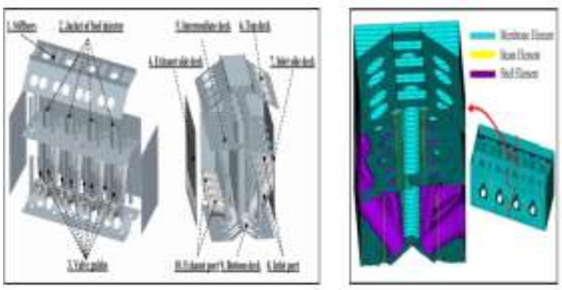


Fig. 1. Flowchart of the optimal design procedure for engine cylinder head.

This section presents an optimal design procedure for the engine cylinder head. It involves three major steps; namely, simplification of the cylinder head model, investigation of structural characteristics and optimization of the cylinder head structure. Fig. 1 shows the system architecture of this procedure. In the first step, a simplified topological model is developed to handle the complications of the mechanical structure and boundary conditions considered in the numerical simulation. Details of the effort include topological model definition, thermal-mechanical analysis, and validation of the simplified FE model. The next step is the investigation of the structural characteristics. The simplified model established in the first step is further developed into a series of different model states. With these models, the parametric analysis is conducted to study the stress convergence characteristics of different key components. Analytical results indicate that there exists an ideal 'balanced point' among the main parameters of the cylinder head. In the third step, a simple and practical optimization criterion is developed based on Lagrange conditions. This criterion represents the ideal 'balanced point' in terms of weight distribution of the key components, and then the optimization of the cylinder head structure can be achieved based on these findings.

3. A simplified topological representation of cylinder head

To truly get an effective simplified model, thought should be given to the key components within the cylinder head, such as their dimensions and the complex geometrical relationships between them. Under the premise of unchanged topological relationships between these key components, a simplified model is extracted from the previous detailed model by using shell, beam and membrane structure instead of the original solid structure, as shown in Fig. 2.



(a) Simplified CAD model (b) Simplified FE model

Fig. 2. The simplified topological model of cylinder head.

The simplified model can be divided into ten parts, including external supporting components (such as bottom deck, top deck, inlet/exhaust side decks) and internal functional components (such as jacket of spark plug, inlet/exhaust ports, intermediate deck, valve guides and stiffeners). There is no other redundant geometrical structure in this model. Because the deformation of the cylinder head is mainly caused by thermal stress, the primary target of the simulation is to precisely predict temperature distribution.

In addition to thermal load, the cylinder head has to endure pre-tightening force and gas pressure. For this case, the maximum pressure of 6.5 MPa is applied to cylinder 3, and the same action is then performed for the other cylinders. Meanwhile, to capture the pre-tightening effect on cylinder head, a required compressive axial load (60 KN) is imposed on the bolt bodies, and the contact elements are applied on the interfaces between the cylinder head, bolts, and gasket. Considering the specified loads originating from different kinds of mechanics, the simulation procedure could be further divided into three load steps: (1) pre-tightening load step, (2) thermal load step and (3) gas pressure load step. Fig. 3 provides details about the coupled thermal-mechanical simulation procedure. Since high temperature and stress gradients are anticipated in and around the valve bridge area, the small and sensitive regions are meshed with high resolution (i.e., the element aspect ratio is approximately 2.0). The completed FE model contains 55 152 elements and 62 816 nodes. To accurately represent the boundary conditions applied on the simplified structure, a parametric-oriented FE model was developed and implemented through an author-written APDL subroutine. Fig. 4 shows the comparison of structural responses between the detailed and simplified FE models.

4. Investigation of the structural characteristics of cylinder head

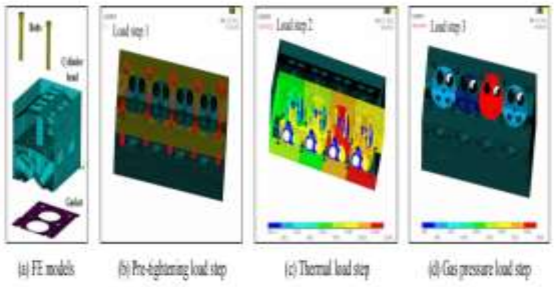


Fig. 3. Sequentially coupled thermal-mechanical simulation procedure

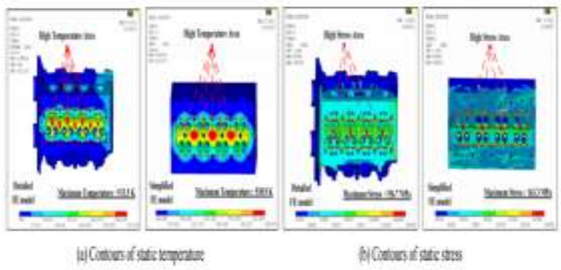


Fig. 4. Comparison of the structural responses between the detailed and simplified FE models.

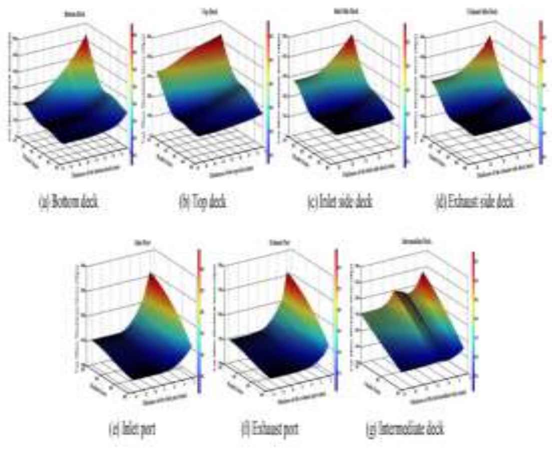


Fig. 5. Influence of the key components' thickness on the Von Mises maximum stress.

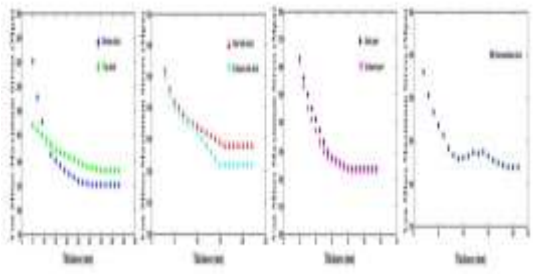


Fig. 6. The stress convergence profiles of different key components in M6.

5. Conclusions

This study is an initial attempt to search for a concrete and practical procedure for the optimal design of engine cylinder head. A simplified topological model composed of beam, shell and membrane elements is developed to simulate the real cylinder head. With this model, the finite element method can be easily and economically employed to conduct the parametric analysis. Calculation results indicate that the increase of the key component's thickness will eventually lead to a stress convergence on the cylinder head. However, different components have different convergence values. This shows that there exists an ideal 'balanced point' among the key components. A simple and practical optimization criterion is then developed based on Lagrange conditions. This criterion represents the ideal 'balanced point' in terms of weight distribution of the key components. Compared with the optimization result from the commercial software, the proposed approach is able to produce a much better solution in respect of both the convergence speed and the final value of the objective function.

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