

New Theoretical Approach for Weight Reduction on Cylinder Head

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ABSTRACT

Designing a lightweight and durable engine is universally important from the standpoints of fuel economy, vehicle dynamics and cost. However, it is challenging to theoretically find an optimal solution which meets both requirements in products such as the cylinder head, to which various thermal loads and mechanical loads are simultaneously applied.

In our research, we focused on “non-parametric optimization” and attempted to establish a new design approach derived from the weight reduction of a cylinder head. Our optimization process consists of topology optimization and shape optimization. In the topology optimization process, we explored an optimal structure with the theoretically-highest stiffness in the given design space. This is to provide an efficient structure for pursuing both lightweight and durable characteristics in the subsequent shape optimization process. The shape optimization process used the result achieved in the topology optimization to obtain a detailed shape having lightweight properties while satisfying high-cycle fatigue strength by coupling it with the fatigue analysis software. In addition to the requirement of high-cycle fatigue strength, various constraints were taken into account simultaneously such as functional constraints including gasket contact pressure and manufacturing constraints including minimum wall thickness or demolding.

As the results of this optimization research demonstrate, 14% weight reduction from a cylinder head designed by conventional means was accomplished. This result validates that the established approach is both practical and effective at reducing the weight of the cylinder head with fulfilling a variety of requirements in design.

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1. INTRODUCTION

It is a universal theme to pursue how lightweight and durable components of engine will be designed. Weight reduction contributes to fuel economy, vehicle dynamics and cost. Recently, a variety of fuel economy standards are imposed [1, 2] and increased attention is focused on lightweight design of automobile components including engines from the standpoint of low fuel consumption.

Increased application of components such as turbochargers, EGR(Exhaust Gas Recirculation) systems, direct injection systems and variable valve trains have counteracted weight reduction strategies. Therefore, designing the basic engine components such as cylinder heads or cylinder blocks to be lightweight becomes more important. In a component which is subjected to thermal and mechanical loads simultaneously such as the cylinder head, it is very challenging to satisfy both required functions and weight reduction. For this reason, the technology of a theoretical approach to get an optimum solution makes a breakthrough in engine weight reduction.

2. CHALLENGES IN CYLINDER HEAD DESIGN

2.1. Function of Cylinder Head

Figure 1 illustrates the structure of a cylinder head. The cylinder head is one of the basic engine components with many requirements to be taken into account during design. For the cylinder head, both requirements of sufficient function and durability must be satisfied. So the structure becomes complicated, which makes the design challenging.

i. Required function

A cylinder head which makes up the combustion chamber performs gas exchange in a cycle by inletting and exhausting gas. Since a combustion chamber is over both cylinder head and cylinder block, the interface must seal the combustion gas. Additionally the cylinder head needs to cool down a combustion chamber, joining ports and valves, and to supply oil to lubricate and drive a valve train.

ii. Durability

The cylinder head is repeatedly subjected to heat and pressure from the combustion simultaneously. That is, the cylinder head needs durability against two different types of fatigue of materials, high cycle fatigue and low cycle fatigue. High cycle fatigue represents the fatigue which is caused by high-cyclic loading such as combustion pressure and low cycle fatigue represents the fatigue caused by repeated low cycle loading such as hot and cold cycles according to engine driving modes.

iii. Structure

The cylinder head includes the combustion chamber, intake, and exhaust ports. It also provides intake and exhaust valves which control gas flow and the structure to hold the valve train which drives them. At the interface to the cylinder block, a gasket is held between them to seal gas pressure. The combustion chamber and exhaust port which are exposed to extreme heat are provided with a cooling jacket to cool them down. In addition, an oil gallery is provided to supply oil to the valve train. The space where coolant or oil is put in is formed by using a core or machining, and must prevent not only leakage from the cylinder head but also mixing coolant with oil.

on the basis of the results until the model achieves the durability requirements. However, this approach has a concern that a number of repetitions will have a limitation in man-hours. Additionally it is basically difficult to verify if the planned basic concept is appropriate or not from the standpoint of weight reduction.

The attempt of introducing parametric optimization to the design engineering of engine components was tried in terms of breaking through the limitation in man-hours for designing and verifying in order to explore a solution efficiently [3, 4, 5]. The parametric optimization can be applied to a subject that can be controlled with parameters such as dimensions and location of shape. But it is not effective for a subject that cannot be controlled by parameter such as judgment if a hole or a rib is needed or not, thus, it is not possible to provide a broad-ranging optimization on the component structure. From here out, it is not ideal to utilize parametric optimization for components with complicated structures such as cylinder heads as an approach of exploring a structural concept effective to weight reduction.

3. OPTIMIZATION OF CYLINDER HEAD STRUCTURE

3.1. Applying Non-Parametric Optimization

We propose that utilizing non-parametric optimization is suitable for designing lightweight and durable component shapes efficiently and theoretically. SIMULIA Tosca Structure was the software used for structural optimization.

We have established the approach of exploring component shapes of low weight and high durability using non-parametric optimization. Then we have applied this approach to the design of engine cylinder heads and have validated the effectiveness. A cylinder head which was designed in accordance with the conventional procedure (hereafter referred to current state model) was used for comparison to verify the results.

In the structural optimization, we have taken high cycle fatigue into account as a criterion of durability and gasket contact pressure for required function. Additionally the minimum thickness of the model and requirements relating to demolding in casting were taken into account as manufacturing constraints because the resultant shape should be manufacturable (Fig. 2).

Figure 3 shows the workflow of structural optimization. The approach consists of topology optimization and shape optimization. First, a theoretically highest stiffness structure is explored in the given design space using topology optimization. This is the reason that the structure to explore both low weight and high durability will be offered for the subsequent process of shape optimization. In the process of shape optimization, a detailed shape that realizes weight reduction with the required durability will be obtained on the basis of the results acquired in the topology optimization by coupling with fatigue analysis solver.

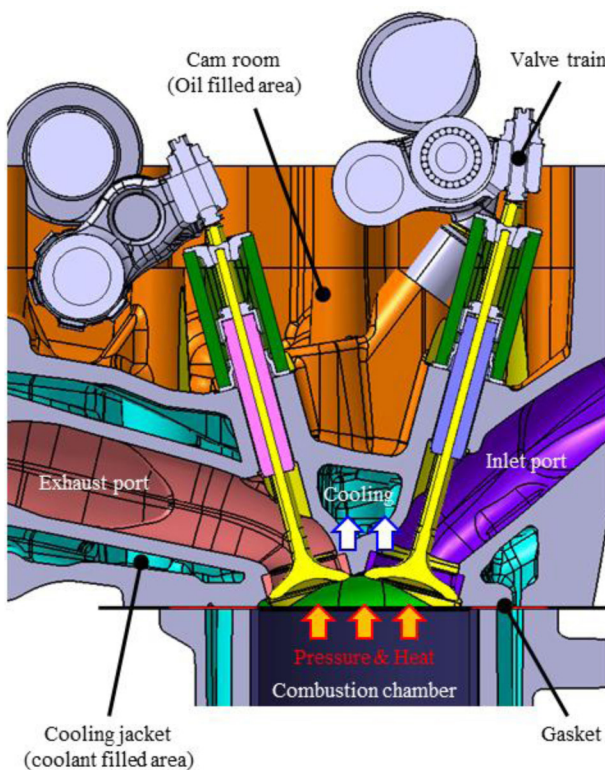


Figure 1. Example of cylinder head structure

2.2. Challenges in Conventional Design Approach

A design engineer will generally intend to design a cylinder head to offer high performance and sufficient durability with simple structure to the extent that's possible. A basic concept of structure is created in the early phase of design, structural analyses and fatigue analyses are performed, and after a number of repetitions modification is repeated

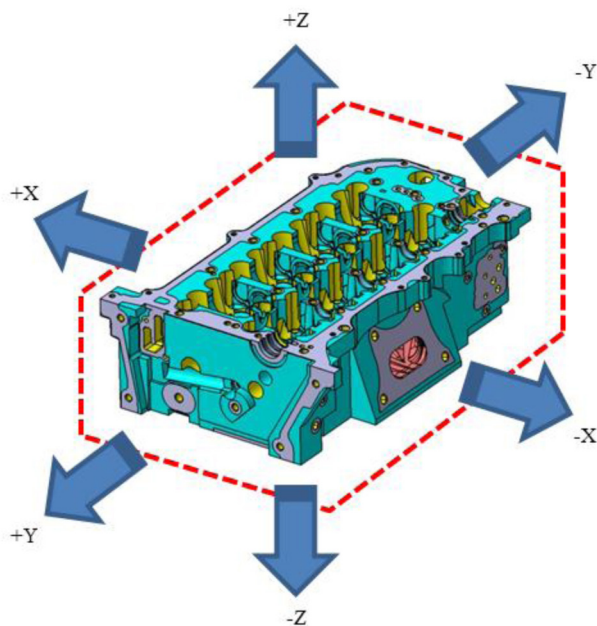


Figure 2. Manufacturing constraints on demolding

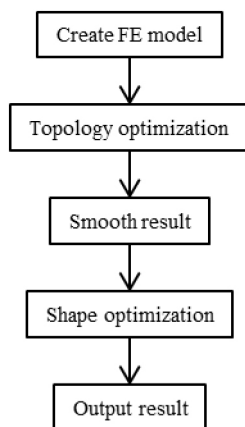


Figure 3. Workflow of optimization

3.2. Outline of Non-Parametric Optimization

3.2.1. Optimization Methods

The CAE-based optimization methods can be roughly classified in two major groups: parametric and non-parametric. As shown in Figure 4, increasing the number of design variables leads to a more optimum solution. Using a parametric approach where each design variable is defined as parameter often limits the explored design space or may lead to very high computational efforts in case many parameters are considered. Non-parametric methods allow a higher amount of design variables, where no parameterization of the finite element model (hereafter referred to FE model) is necessary, thus offering more design flexibility.

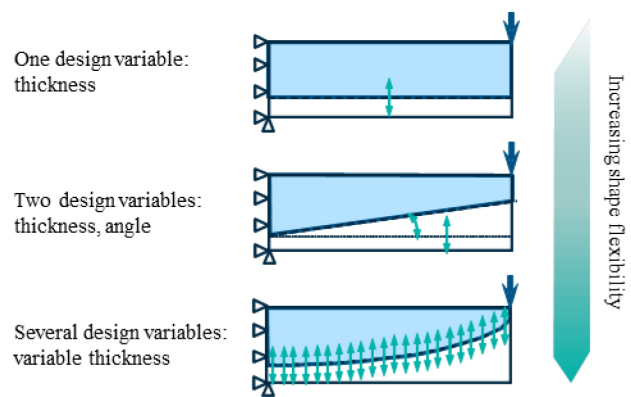


Figure 4. Example for modification of a structure

3.2.2. Topology Optimization

One of the most popular and widely used optimization approaches is the non-parametric topology optimization. Topology optimization is frequently used in the early design phase producing new design suggestions where the optimization targets could be to obtain desirable stiffness properties and fulfill mass constraints. Usually, topology optimization provides the ability to yield correct decisions in the early mechanical design phase.

The concept behind the topology optimization is shown in Figure 5. Based on an FE model containing the geometrical design space and under consideration of given loadings and boundary conditions, the topology optimization determines which elements contribute to the global stiffness of the structure and would hence represent the new material distribution, and those that can be eliminated from the design space. As described in [6], for realization of this concept, the elemental relative density ρ_e of each individual structural finite element in the FE model is defined as design variable. These new design variables can be solid (relative density at upper limit: $\rho_e = 1$) or void (relative density at minimum limit: $\rho_e = \rho_{min} \sim 0$). The so-called SIMP-model, described in [7], is applied for modeling the elemental stiffness as being proportional to a power-law of the relative elemental density.

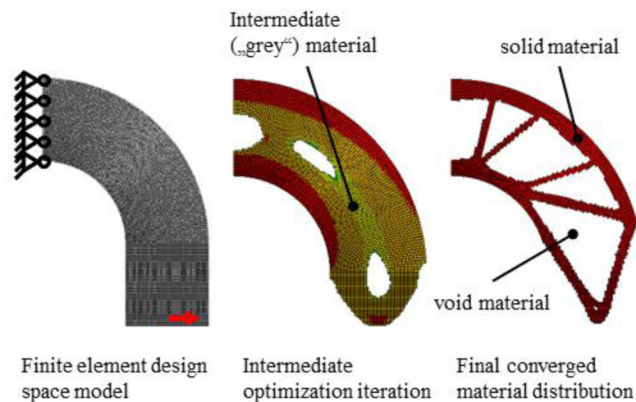


Figure 5. Scheme of non-parametric topology optimization

Different optimization algorithms exist for topology optimization. Some of the most commonly used are the optimality criteria and mathematical programming methods. The main differences in those