A multi-disciplinary approach for design improvement of an air-cooled two-wheeler engine cylinder head

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ABSTRACT

The air-cooled engine surfaces are generally provided with extended surfaces of high conducting materials called fins for enhanced heat transfer. One way to increase the rate of heat transfer is by increasing the fins surface area. However, increase in fin length introduces undesirable vibrations of the fins, which in turn radiate annoying high frequency noise. With the demand of quieter engines increasing, the vehicle manufacturers follow counter measures to minimize the fin vibrations. One trend in the two-wheeler industry is to put rubber dampers between the fins. These rubber dampers damp out the level of vibrations and the level of noise radiated is reduced. However, these rubber dampers have many disadvantages. Apart from the adding extra cost and a parallel manufacture process, these rubbers act as an insulating material, which impede the free flow of cooling air. The engine may get overheated and purpose of providing extended surface would not be satisfied.

In this paper, effect of these rubber dampers on engine radiated noise and thermal performance is investigated. We discuss a systematic methodology on how to remove these rubbers by keeping the noise level same along with higher heat transfer from the engine surfaces. Results from experiments and numerical simulations for noise & vibration and computation fluid dynamics (CFD) with conjugate heat transfer are discussed. This paper describes a classic example of multi-disciplinary approach to solve real-world design problems.

INTRODUCTION

Extended surfaces are provided on the air-cooled engines for heat dissipation to the ambient. These extended surfaces are called fins. More surface area is desirable for higher heat dissipation from these surfaces. However, apart from the above requirements, noise radiated by the fins is also one of the concern areas for design engineers. Fins are the thin extended surfaces that are provided for cooling the engine. Fins vibrate when engine runs at higher speeds and this vibration in turn produces undesirable noise. Hence, a thermally better design of the engine is not necessarily a better design from the noise point of view. With the advancement of technology customers now seek more quieter engines for better comfort level [2-4]. One of the methods adopted in the design of air-cooled engines is to provide rubber dampers between the fins to reduce the noise radiated by the fins. Though the level of noise radiated by fins is reduced with this method, this comes with extra cost. Also, the presence of these rubber dampers hampers the cooling of the engine head by air. With raw material, such as steel and aluminum, cost, increasing day-by-day, rubber dampers add to the extra cost and hit the company’s profit margins. Hence, effort has to be made to design the engine, which should involve less or no rubber dampers while meeting all the requirements of an engine.
In this paper we have considered a two-wheeler small piston displacement engine cylinder head (see figure 1), which has dampers between the fins. This work is undertaken to redesign the cylinder head so that all the rubber dampers can be removed while satisfying the noise and thermal characteristics of the existing cylinder head. There is not much information available in the scientific literature to improve the engine cylinder head design from noise as well as thermal point of view. E.g. Takahashi and Gokan [5] studied the effect of different fin designs on the enhancement of engine heat transfer. Thornhill et. al [6] investigated the effect of various fin lengths, thickness and fin spacing on cooling performance of air-cooled cylinders. In this paper, we address the issue of noise, vibration and thermal performance of air-cooled cylinder head and methodology for design improvements. The systematic procedure followed has been described in the subsequent sections. Experiments, Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) are carried out to study the thermal behavior and noise radiated by the engines. FEA was used to conduct modal analysis where as CFD was used to study the effect of rubber dampers on the temperatures of engine.

EXPERIMENTAL NOISE MEASUREMENT

Noise radiated by the engine is measured in a semi-anechoic chamber. Quantification of noise levels with and without rubber dampers on the cylinder head was done systematically. There were 16 dampers on the cylinder head. We systematically removed 4 dampers each time and the engine was run varying the speed from 0 to 6000 RPM. Hence the noise was measured with 16, 12, 8, 4 and 0 (all dampers removed) dampers. We have shown only the results of 16 and 0 dampers for clarity. Figure 2 shows noise radiated by the engine with 16 and 0 dampers. Clearly, noise radiated by the engine when no dampers are present is higher than with dampers. The fins radiate an average of 3 dB higher noises when no dampers are used. Hence, the cylinder head needs structural modifications if dampers are to be removed completely from the cylinder head. FEA was used to study the vibration modes of the cylinder head fins. Modal analysis was carried out. Based on the FEA results, design modifications were carried out on the cylinder head. The final design without rubber dampers was tested experimentally in the semi-anechoic chamber. Further, CFD analysis was performed on the final design to study the temperature variations on the cylinder head and block due to of rubber dampers. These dampers obstruct the flow and increase the engine temperature.
FINITE ELEMENT ANALYSIS

In this paper, both dynamic and thermal analysis has been presented. We will briefly discuss the boundary conditions applied for both the analysis. Geometry clean up and meshing is done using HyperMesh while all the analysis has been done using ANSYS, which uses the Finite Element Method (FEM) [7].

Modal and harmonic response analysis

The Mass matrix \([M]\), stiffness matrix \([K]\) is formulated by considering ideal structures [1]. Eigen values and Eigen vectors are obtained by modal analysis. The equations of motion is written as

\[
[M]\{x\} + [K]\{x\} = 0
\]

where \(\{x\}\) represents generalized nodal displacement. In vibration analysis, displacement and other derived quantities varies with time, which are sinusoidal in nature. The equation of motion that satisfies equation (1) can be written in the following simple harmonic form as

\[
\{x\} = \{X\} \sin(\omega t)
\]

Putting (2) in (1), we have,

\[
[K]\{X\} = \lambda[M]\{X\}
\]

Here the eigen value \(\lambda = w^2\). The eigen values determine the natural frequencies while eigen vectors give the mode shapes corresponding to each natural frequency. A finite element model of the cylinder head is prepared and appropriate boundary conditions are applied. We have not simulated the case with rubber dampers. All the modal analysis in ANSYS was run without rubber dampers. Modeling rubber dampers would involve non-linear analysis, which requires more computational time and resources. Base of cylinder head was fixed for all degrees of freedom for doing modal analysis. Solid element 45 was used for meshing the cylinder head in ANSYS. Element solid 45 is used for the three-dimensional modeling of solid structures. Eight nodes having three degrees of freedom at each node define the element: translations in the nodal x, y, and z directions. Properties of aluminum are used. The value Young’s modulus of elasticity equal to 73000 MPa and density equal to 2790 kg/m³ was used. Modal analysis was followed by harmonic response analysis for each modification. In harmonic analysis, mode superposition method with excitation of 6.8 times of gravity in vertical direction was applied to the model. Damping ratio of 2% was used. Amplitude of vibration of fins

![Figure 2. Comparison of noise radiated from the engines with and without rubber dampers on the cylinder head at 3150 Hz.](image)
was investigated for each modification. Decrease in the amplitude of vibration was considered as the desired output from the design modifications on the cylinder head.

Results

The CAD model of the existing cylinder head is shown in figure 3(a). A metal strip has connected at the base of the fins and rubber dampers are provided between the fins (see figure 1). Results from the modal analysis are shown in figure 3(b). Only the first mode of vibration is shown. It shows that fins at the middle (red colored) are
having local modes of vibration with first mode natural frequency of 2204 Hz. Shorter fins that are connected to the combustion surface directly exhibit the local modes. Hence, the target in the new design of the cylinder head fins was to convert the local modes into global modes and to increase the first mode natural frequency of vibration. Several modifications on the cylinder head fins designs were made. Modal analysis was conducted for each design and the first mode natural frequency was monitored. Figure 4(a) shows the final design of the cylinder head. The thin metal strip was extended from top to bottom of the fins. Figure 4(b) shows the first mode of vibration. The natural frequency has increased to 4134 Hz, which is 88% higher than the existing old

Figure 5. (a) Amplitude of vibration of the fins on the base cylinder head (b) amplitude of vibration of fins on the modified cylinder head obtained from harmonic response analysis.
design. Further, the local modes of vibration that observed in the old design is not exhibited is this design and the modes of vibration is global. Figure 5 shows the amplitude of vibration of the fins on two designs of the cylinder head. Top and bottom fins in legend means that the amplitude of vibration was calculated at the top and bottom position of the fins (see figure 4a). The top fins in the existing cylinder vibrate with higher amplitudes than the bottom fins (figure 5a). In the modified cylinder head, both the top and bottom fins vibrate with almost equal amplitude with reduced magnitude. There is about 20 times decrease in the amplitude of vibration in the new design. A prototype was made of this new design and tested in the laboratory for the radiated noise for comparison with the existing design of the head.

![Figure 5. Comparison of amplitude of vibration of fins on two designs of the cylinder head.](image)

The figure clearly shows that the final design is as good as the first design. The noise radiated by the new design is same compared to the old design across the engine speed. Hence, the old design of the cylinder head with rubber dampers can be replaced by the new design without rubber dampers.

**Laboratory experiment**

Laboratory experiments are conducted to measure the noise pressure level on the old and the final design of the cylinder head. Notice that in laboratory testing, old cylinder head has all the rubber dampers where as in the new design has no dampers. Figure 6 demonstrates the noise pressure level radiated by the old and the final design.

**Cost and environmental impact**

The increase in the mass of the new design of the cylinder head was about 40 gram more than the existing cylinder head. This increase in mass was due to the extension of the metal plate (cf. figure 2 and 3). Thicknesses of the fins were remained unchanged. In spite of the increase in insignificant mass, the major benefit of the new design is that no rubber dampers will be used. Following are the few advantages: (i) rubber damper manufacturing process is eliminated; rubber production is harmful to the environment (ii) logistic reduction (iii)
man power saving (iv) inventory reduction (v) part count reduction; from 17 parts (16 dampers and 1 cylinder head) to 1 part (only cylinder head).

**COMPUTATIONAL FLUID DYNAMICS ANALYSIS**

**Thermal analysis**

Thermal analysis was carried out to determine the effect of rubber dampers on the temperatures of cylinder head and block. Conjugate heat transfer analysis was performed. The engine was put into a wind tunnel (figure 7). Inlet velocity of 50 km/hr was provided. Atmospheric boundary was provided at the outlet. Two cases were run. One case with all the rubber dampers on the cylinder head and another without rubber dampers. A uniform heat flux of 221.3 kW/m² was applied on the combustion chamber of cylinder head and 216 kW/m² on the liner of the block. The commercially available CFD software Star CCM+ was used for simulations.

Figure 7. CFD model setup of engine head and block. Rubber dampers are between the fins.
Results

Now, we present the results from the thermal analysis obtained from conjugate heat transfer. To illustrate the effect of rubber dampers on heat transfer from the engines, temperature contours are shown on the same range. Figure 8 illustrates the temperature contours on the cylinder head with and without rubber dampers. It can be noticed that hot zone in the cylinder head with rubber dampers is more than the cylinder head without dampers. Volume averaged temperature of the cylinder heads in both the cases reveals that cylinder with rubber dampers has about 10°C higher temperature than the cylinder head without the dampers. Rubber dampers acts as an obstructing medium for air flow which affects cooling. This new cylinder head without rubber dampers was implemented for the mass production of the vehicles.

CONCLUSIONS

In paper, we have presented a case study to improve the design of the cylinder head from noise and thermal point of view. The main aim of this work was to improve the design of the cylinder head from noise, vibration and thermal point of view so that the need of putting rubbers dampers is eliminated. These rubber dampers involve extra cost to the product. Experimental measurements as well as numerical simulations were carried out to verify the design improvements. We systematically carried out design modifications and simulation is carried out at each stage (without dampers) to calculate the increase in natural frequencies of vibration and decrease in the amplitude of fin vibration. We found 88% increase in the first mode frequency of the fins in the final design from the baseline design. Experiments in the semi-anechoic chamber reveals that cylinder head with rubber dampers has similar noise characteristics as that without dampers. Heat transfer analysis shows that cooling is improved when no dampers are present on the engine head We feel that this work will help the design engineers in automotive industries to carryout this process to improve their engine’s thermal and noise performance.
REFERENCES