Reduction of Cylinder Bore Deformation in Engine Assembled Condition for a Single Cylinder Gasoline Engine

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Abstract: India being a country with one of the maximum two wheeler density in the world, all the scooter and bike manufacturers are fighting to keep their market share by quickly bringing quality products with high mileage at a cheap price tag. Emission norms are also becoming stringent day by day. Hence, they should take care of every detail in the Internal Combustion engine driving their vehicles. So today's engineer must be efficient and they must be able to refine and improve the technologies they use, faster and with greater accuracy than ever before. This paper is concerned with reducing Cylinder Bore deformation through CAE simulation which can cause engine seizure in extreme conditions. Liner deformation is of great significance to the overall performance of an engine in terms of oil consumption, blowby, emissions and influences piston dynamics to a great extent. They are however, difficult to measure and the results which are in micron level are often prone to misinterpretation. Moreover, making physical prototypes with frequent design changes to reduce bore deformation is highly time consuming and costly exercise since it involves most critical engine parts which are often high lead time items in engine development cycle. Therefore, to cut down the design cycle time, virtual simulation methods are preferred.

The objective of this study is to evaluate and reduce deformation of cylinder liner of a high cubic capacity gasoline engine in assembled condition using the capabilities of SIMULIA ABAQUS, a world-wide leader for simulating complex problems on engine durability. Due to unavailability of a default template in ABAQUS CAE/VIEWER to measure liner deformation, a manual node-set and cut-section based calculation was developed to calculate approximate values of deformation of the liner. The cylinder head assembly comprising of major components like head, block, gaskets, liner, etc. is meshed with second order tetrahedral element and the analysis model is set up in ABAQUS CAE. The base design was then subjected only to bolt pretension loads for evaluating liner deformation. Based on the FE analysis done, scope to reduce liner deformation was observed. Subsequently, a number of design modifications were made and simulated using ABAQUS in a similar way to reach a final proposal which gave acceptable deformation. The comparative results of the final proposal indicate a useful reduction in deformation in the localized liner area, from the base design, without affecting stress and stiffness in other areas. It is expected that this paper will serve as a good reference for engineers who are targeting to reduce liner deformation in their engines.

Keywords: Gasoline Engine, Liner Deformation, Bolt Loads, ABAQUS CAE

Introduction

cylinder bore distortion due to the application of bolt pretension and/or thermal loads is termed as cylinder bore deformation. These distortions occur in harmonic form and generally are of several distinct orders. Each of these orders represents a sinusoidal curve. The final deformation obtained may be a combination of one or more of these orders. Bore deformation can occur in different engine components (Figure 1).

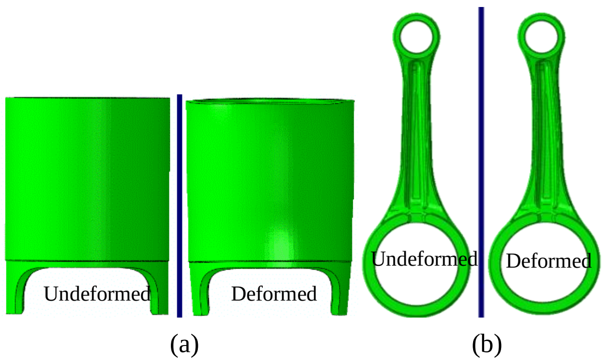

Figure 1. An Example of bore deformation on various engine subsystems

Here, in this paper the discussion is restricted to liner bore deformation which is considered to be very essential for smooth functioning of an engine. It may cause blowby, piston scuffing and excess oil consumption if left unattended "(Mirajkar, 2013)". Figure 2 below shows various patterns of bore deformation in a discrete manner.

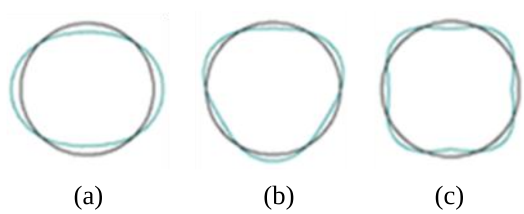

Figure 2. Distinct orders of Bore deformation

High bolt torqueing and greater in cylinder combustion pressure are inherent in diesel engines and thus they are usually affected by bore deformation.. Two wheelers, on the other hand, are in general driven by fast gasoline engines with lighter parts and comes with the added restrictions on space and packaging. This paper is aimed to provide a holistic overview on the iterative design methodology undertaken to reduce excessive liner deformation for a high cubic capacity gasoline engine.

Theory

"(Tomanik, 1996)" has explained that the deviation from a circular shape of the bore can be mathematically described by a Fourier series as:

$$D_r = A_0 + A_1\cos(\theta) + A_2\cos(2\theta) + \cdots + A_i\cos(i\theta) + B_1\sin(\theta) + B_2\sin(2\theta) + \cdots + B_i\sin(i\theta) \quad (1)$$

where,

D_r : Radial deviation from the circle
A_i, B_i : Fourier coefficients
θ : Angular position
i : Order of deformation, $i = 1,2,3,\dots,n$

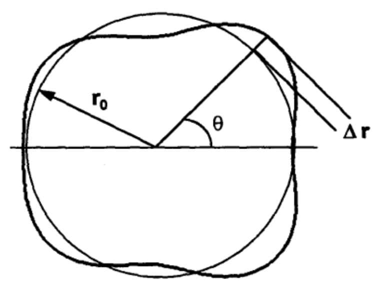

Figure 3. Cross Section of deformed Bore (Picture Source: "(Tomanik, 1996)")

At each order i, the maximum deformation of the cylinder (or amplitude): u_{bi} and the angle (or phase, Figure 3): $\emptyset_{bi}$ where it occurs, can be calculated through the Fourier coefficients:

$$u_{bi} = 2\sqrt{(A_i^2 + B_i^2)} \quad (2)$$

$$\emptyset_{bi} = \left({}^{1}/_{i}\right)\arctan\left(\frac{B_i}{A_i}\right) \quad (3)$$

Then, the radial cylinder deformation (Δr) can be described by a Harmonic series as

$$\Delta r = A_0 + \sum_{i=1}^{n}\left[\frac{u_{bi}}{2}\cos\{i(\theta - \emptyset_{bi})\}\right] \quad (4)$$

FEA Analysis of the Engine Base Design

FEA analysis has always been useful for simulating large number of design iteration within a short time span. The renowned commercially available numerical code Abaqus CAE 6.12 was used to analyze all the design proposals referred in this paper. At first, the base engine model was prepared in a modelling software with accurate tolerances (Figure 4). To replicate the exact testing conditions, half crankcases were considered.

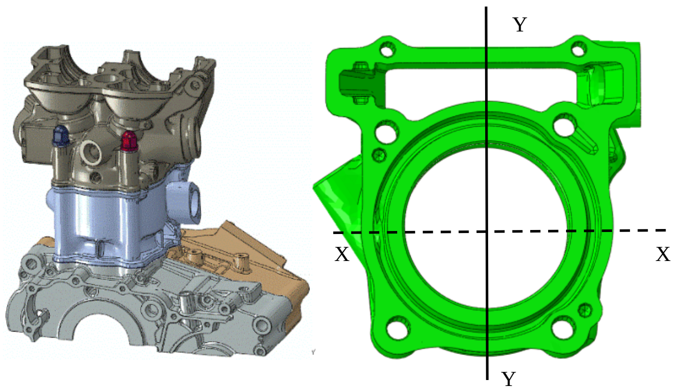

Figure 4. CAD model

Numerical Discretization or Meshing

Fine meshing required to capture micron level bore deformation was then done with tetrahedral second order (C3D10) elements (Figure 5) for all components (including head, block, liner, crankcases, studs, nuts and bolts) except the gaskets. Gaskets between head and block and between block and crankcases were carefully meshed with linear hexahedral elements of type (C3D8R) and linear wedge elements of type (C3D6). This was done to avoid any kind of mesh interference between the mating components. Owing to high nonlinearity of the problem, mapped mesh was ensured between all the mating parts to avoid penetration error while solving. Mesh element size and number of elements on the liner was created in such a way that the measurements can be taken at perfect XX and YY plane, thus replicating testing conditions.

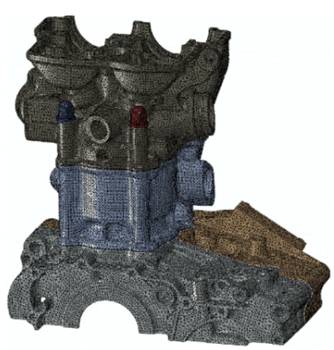

Figure 5. Meshed Model

Material Properties

The completely meshed engine model was fed into FEA simulation code. Material properties were defined in the pre-processor as per Table 1. Material non-linearities were considered for ADC12 and Steel components as per various standards and available in-house metallurgical testing. It was tabulated as a plastic stress versus strain data and fed into the materials database of the FEA software. Table 2 shown below represents the material assigned to each component as per design requirement.

Table 1 Material Properties

Sl. No.	Materials	Properties				
		Density	Elasticity		Expansion	Plasticity
			Young's Modulus	Poisson Ratio		
1	ADC12	2.7E-09	71000	0.33	2.04E-05	Defined
2	Steel	7.8E-09	210000	0.3	1.12E-05	
3	Cast Iron	7.2E-09	130000	0.3	1.12E-05	Not Defined
4	Paper Gasket	7.0E-10	4800	0.45	4.50E-06	

Table 2 Properties assigned to different components

Sl. No.	Component(s)	Material
1	Cylinder Head, Cylinder Block, Crankcases	ADC12
2	Bolts (2 in Nos.), Studs , Nuts and Washer (4 in Nos.), Gasket between Cylinder Head-Cylinder Block	Steel
3	Gasket between Cylinder Block-Crankcases	Paper Gasket
4	Liner	Cast Iron

Contact and Boundary Conditions

Both forms of contact, namely interactions and ties were used to define the model. Penalty algorithm with a strain free adjustment was used to define interaction properties. Bolt flange was modelled with finite sliding interaction associated with a judicial selection of co-efficient of friction to better evaluate the flange pressures at the bolt locations. The bolt threads were simulated using a tie with the corresponding mating part. Sliding interaction is defined between gaskets layers and the head and block with surface to surface formulation (Figure 8).

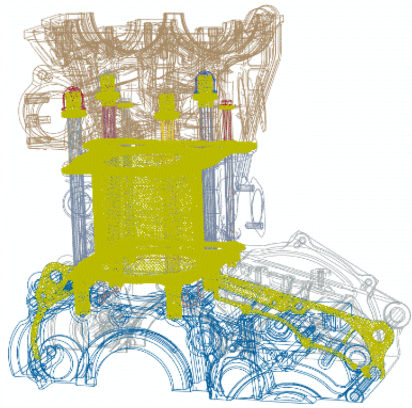

Figure 6. Contact Definitions

Soft springs with a stiffness value of 1 unit was provided for the solver to achieve initial stabilization. The crankcases are held from a set of nodes at their bottom face and all degrees of freedom are arrested to give fixed Boundary conditions.

Load Case

A single load case with bolt pretension loads is used for the analysis. The four M8 studs are given a force equivalent to 5.2 kgm torque. Similarly, two M6 bolts on the chain sprocket side have a force equivalent to 1.1 kgm applied on them (Figure 7).

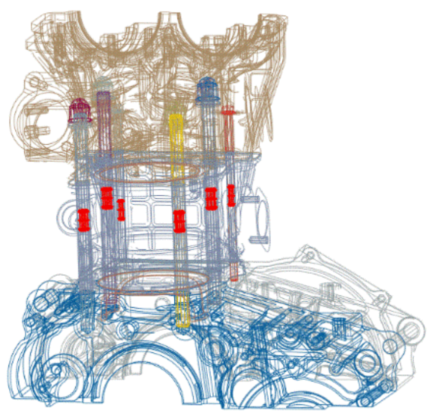

Figure 7. Bolt Pretension Loading

Results on the Base Design

The stress on block and liner was within acceptance. Hence, they were checked for deformation (Figure 8).

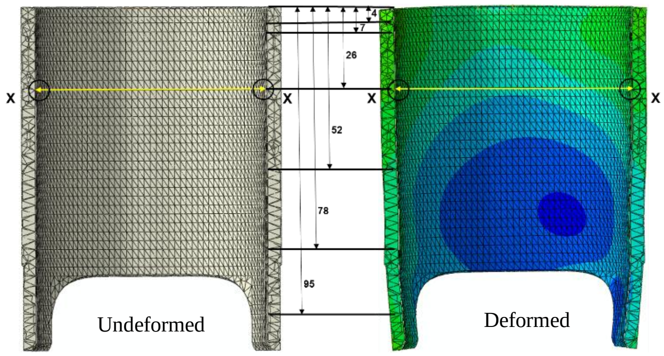

Figure 8. Deformation measurements taken in Abaqus Viewer 6.12

Figure 9 depicts the deformation graphically.

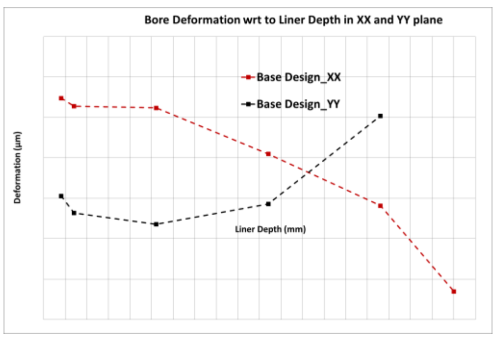

Figure 9. Liner Deformation for Base Design obtained from Simulation

The next section will describe the design modifications done to reduce this excessive deformation.

Design Proposals

The immediate guess taken to reduce liner deformation was to strengthen it by adding material. The base design (Figure 4) had a cut window at the bottom of the liner. This window was filled. Other components remaining as it is, design iteration 1 (Figure 10) was simulated under same loading and boundary conditions.

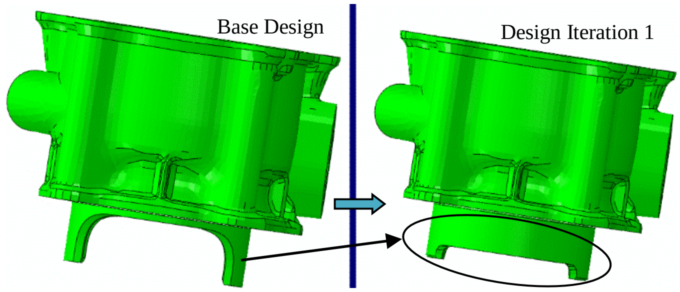

Figure 10. Design Iteration 1

The results were calculated in a similar way as base design and is shown in Figure 11.

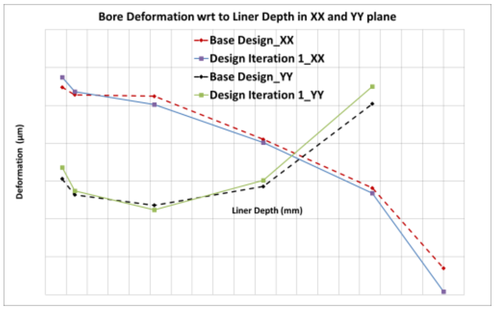

Figure 11. Liner Deformation for Design Iteration 1 obtained from Simulation

As evident from Table 5 adding material at the lower end of the liner deteriorated the bore deformation along both XX and YY plane.

As adding material to the lower end of the liner was not helping, so another proposal named design proposal 2 with base liner's outer diameter radially increased by 1mm (Figure 12) was considered.

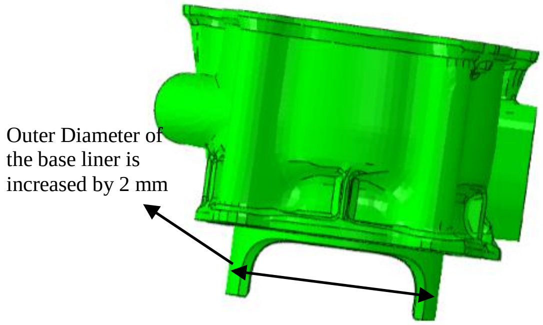

Figure 12. Design Iteration 2

The deformation at the top of the liner was found to reduce on XX plane. However, it was still higher near the BDC zone as shown in Figure 13.

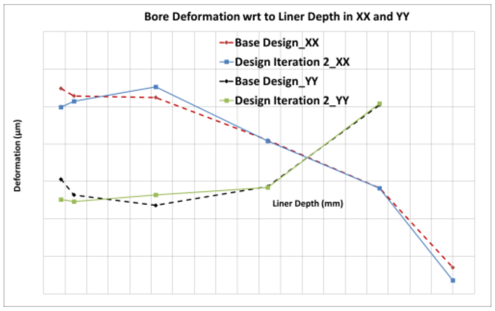

Figure 13. Liner Deformation for Design Iteration 2 obtained from Simulation

Design iteration 2 required to remove material from inner cylinder of the block where liner rests. This resulted in the block becoming weaker. Hence, design proposal 3 (Figure 14) was proposed with the following novel modifications:

- Material Addition : Some ribs and an annular ring was added.
- Material Removal : Material was removed from the block by creating a number of small pockets at the block to crankcase mating interface.

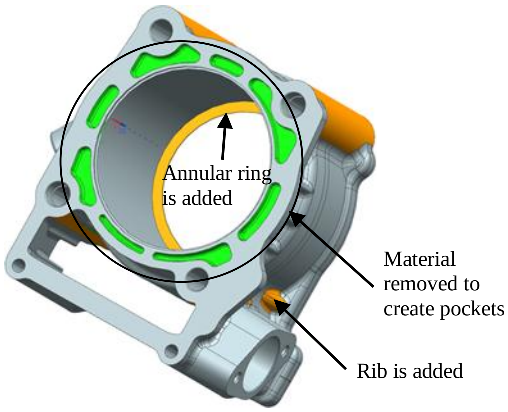

Figure 14. Design Iteration 3

The bore deformation results of Design Iteration 3 are compared to base design in Figure 15.

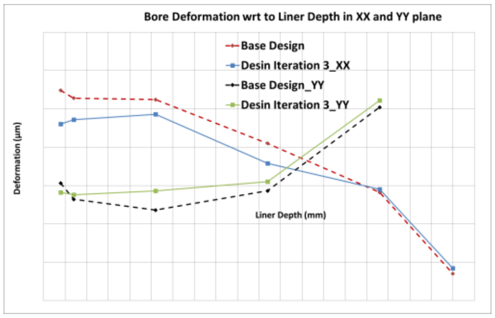

Figure 15. Liner Deformation for Design Iteration 3 obtained from Simulation

Design iteration 3 showed about 7 % improvements in deformation at the bottom of the liner along XX plane.

Optimizing the block and liner design to reduce deformation without adding a lot of weight was the focus of previous three iterations. As these components were finalized, another proposal with modified crankcases (Figure 16) were suggested to achieve the desired deformation reduction target.

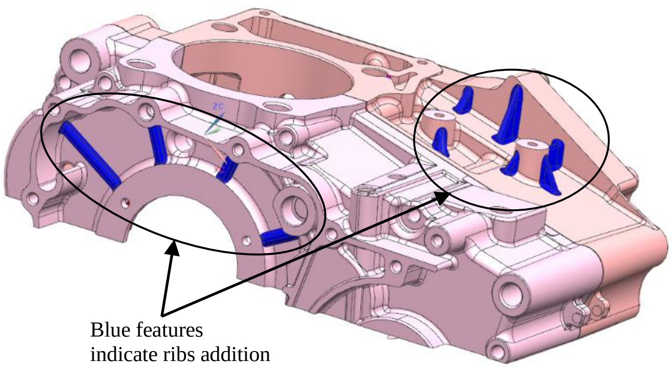

Figure 16. Design Iteration 4

The deformation values obtained for design iteration 4 are given in Figure 17.

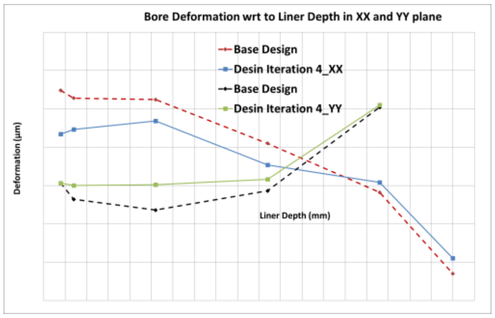

Figure 17. Liner Deformation for Design Iteration 4 obtained from Simulation

Thus, target was met by this final iteration which gave a required deformation reduction at both the top and bottom end of the liner along its XX plane.

Conclusion

The aim of this study was to effectively achieve reduction in liner deformation within a short time duration using Abaqus CAE 6.12. The finalized design gave a reduction of deformation by about 18 % on the critical lower end of XX plane and 46 % on the YY plane respectively. Total weight addition on the system was minimal.

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