Cylinder Head Valve Guide Wear Analysis of Internal Combustion Engine

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ABSTRACT

An analytical process was developed to study the root cause of the exhaust valve guide wear in the gasoline engine from a high mileage accumulation vehicle test. A thermo-structural model was created to determine maximum cam bore misalignment based on engine thermal structural analysis. Then a valve train dynamic model was developed as a submodel based on cylinder head thermal deformation, the cam axis was adjusted based on the maximum cam bore misalignment in this dynamic model and valve tip side load from cam and rocker arm was calculated. Normal and reversed spin of cam was performed to study its effect on rocker motion between left and right bank cylinder heads. Valve and guide contact was monitored during the dynamic analysis and the resulting valve and guide deformation from this dynamic analysis was input to a tribology model to calculate the guide wear rate. Abaqus/Standard was used in thermo-structural analysis, and Abaqus/Explicit was used for valve train dynamic analysis. Based on this study, the root cause of the guide wear was verified.

KEYWORDS
Valve guide wear, thermal structural analysis, Aluminum Alloy, cam bore misalignment, valve train dynamic analysis, FEA simulation

1. INTRODUCTION

In the automobile engine, the function of the valve train is to control the exchange of gas. The valve train includes the intake and exhaust valves, the springs, cam shafts, rocker arms, and other force-transfer devices. The smooth operation of the valve train system**,** particularly between valve stem and valve guide**,** is related to the material used, the mechanical behavior of each component, and the available amount of lubrication. The wear of both components must be low enough at any engine operating condition to ensure the valve train system functions well and produces the desired engine horse power and emissions.

When the valve guide wear issue occurs, one way to resolve it is by increasing the valve to guide clearance or using a high leak rate stem seal to allow more oil flow down the valve stem seal. However, this increase of oil will cause higher oil consumption and affect engine fuel economy. There is a need to understand the root cause of the valve guide wear from the valve train system level, so a more robust cam/rocker/valve system can be comprehended in the upfront engine architecture design phase

In this paper, the study was focused on a high mileage accumulation vehicle that has experienced valve guide wear that led to engine misfire. This type of valve guide wear was not captured in the regular engine durability bench test, but in a modified low speed bench test. The guide wear was seen mainly on the exhaust side of the left bank head in a V6 engine. There is also evidence of side contact on the tang of the exhaust rocker arm on the left bank head, but not on the right bank head. Since the cam shaft has different rotation directions between left bank ('Reverse' rotation) and right bank head ('Normal' rotation), there was a hypothesis that this valve guide wear could be related to the 'Pull me' and 'Push me' mechanics, relative to the SHLA (Stationary Hydraulic Lash Adjuster). This is illustrated in Figure 1. To understand the root cause of the valve guide wear and prove the hypothesis, a finite element based thermal structural analysis and valve train dynamic analysis were performed to calculate and compare the contact pressure between exhaust valve and guide as well as wear index for exhaust valve guide under different engine operating conditions for both left bank and right bank cylinder heads.

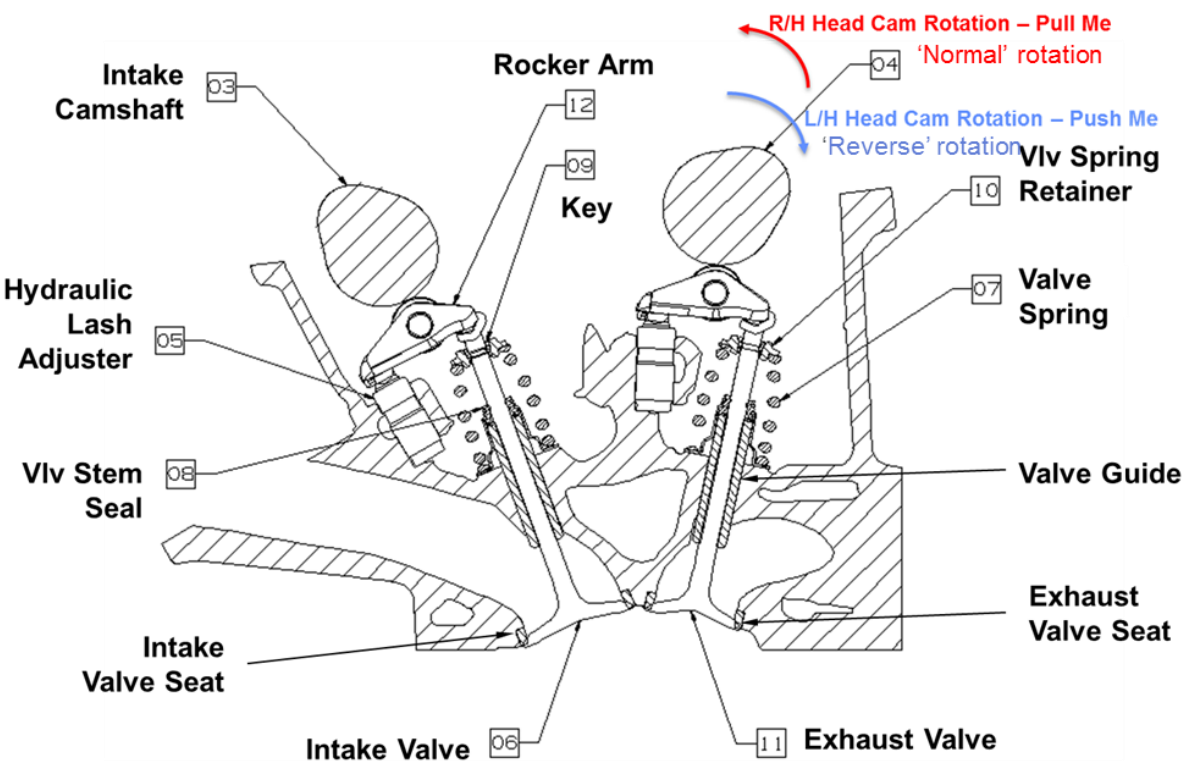

Figure 1: Front view of Left bank cylinder head and valve train cross-section

2. ANALYTICAL MODEL AND ANALYSIS FLOW CHART

Figure 2 shows the analytical model and Figure 3 illustrates the analysis flow chart for the valve guide wear study. Basically, the analysis started with a full V6 engine assembly model that consists of both left bank and right bank cylinder heads, cam bearing caps, head gaskets, cylinder block, main bearing caps, along with the bolts for cam cap and head assembly. Two loading conditions, at peak power RPM (Revolution Per Minute) and low speed (warm idle) bench test conditions, were simulated in this study to compare the results. Besides cylinder head and cam cap assembly load, steady state thermal load, valve train loads that include cam bearing load, fuel pump load and combustion pressure, corresponding to each loading condition, were considered. The outputs from this engine thermal structural analysis related to the valve guide wear are the valve seat and guide distortion, seat-to-guide misalignment, cam bore distortion and misalignment.

After examining the analysis results, the cam bore misalignment was identified to be the key metric that could explain the valve guide wear because the other outputs did not show much difference between different loading conditions as well as between left and right bank cylinder heads. This data then was used as an input for the subsequent valve train dynamic analysis. In this valve train dynamic model, a subset of cylinder head, namely the middle cylinder of the exhaust side cylinder head, was used along with the valve train components such as exhaust valve, valve spring, valve guide and seat, rocker arm, cam lobe of camshaft, SHLA, etc. This is illustrated in Figure 4. The assembly and thermal deformation of the cylinder head, valve seat and guide for this dynamic model were extracted from the full engine thermal structural model for both operating conditions. Valve tip side load from camshaft and rocker arm was also determined in the dynamic analysis, and the cam axis was adjusted based on the maximum adjacent cam bore misalignment.

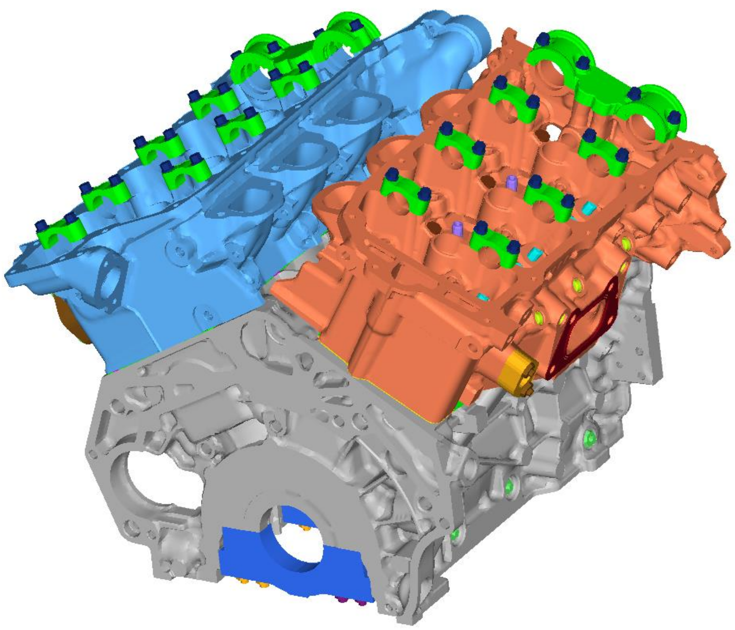

Figure 2: Engine assembly model for global thermal structural analysis

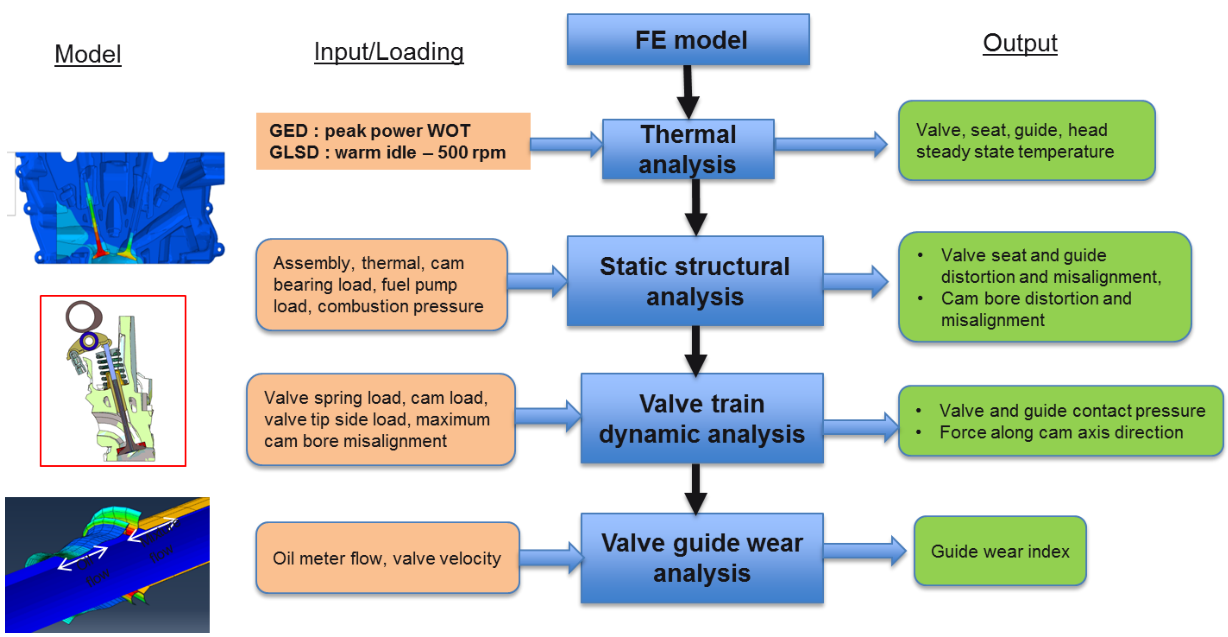

Figure 3: Analysis flow chart for valve guide wear study

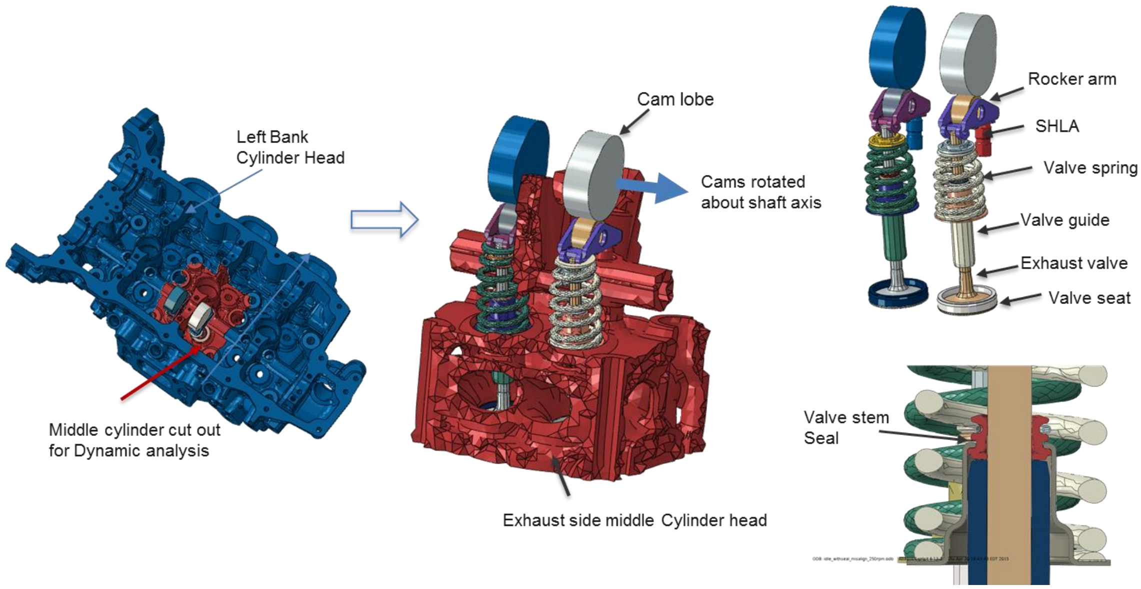

Figure 4: Valve train dynamic model

3. VALVE TRAIN DYNAMIC LOADING

Due to the fact that the valve guide wear was only seen on the left bank cylinder head exhaust side under low speed (warm idle) condition, and there were no guide wear issues from the engine durability test which runs mostly under peak power RPM, high speed condition, it is important to understand the valve train loading between the two engine operating conditions. Figure 5 compares exhaust side cam bearing load and fuel pump load for the left bank cylinder head. These loadings are calculated based on an in-house software that considers valve train kinematic behavior. The loading profile for each individual cam bearing indicated that**,** at peak power or high speed condition, the cam load is driven by 'in-phase' rotational force from cam. 'In-phase' means that at a specific cam rotation angle, the peak cam bearing load can be seen at multiple cam bearings. On the other hand, at warm idle or low speed condition, the cam load is dominated by 'out-of-phase' spring force. 'Out-of-phase' means that at a specific cam rotation angle, only one bearing shows significant cam load comparing to other bearings. The difference of these cam loads could explain why a larger adjacent cam bore misalignment was seen at warm idle condition than at peak power condition as discussed later. Figure 6 shows similar loading profiles for right bank cylinder head.

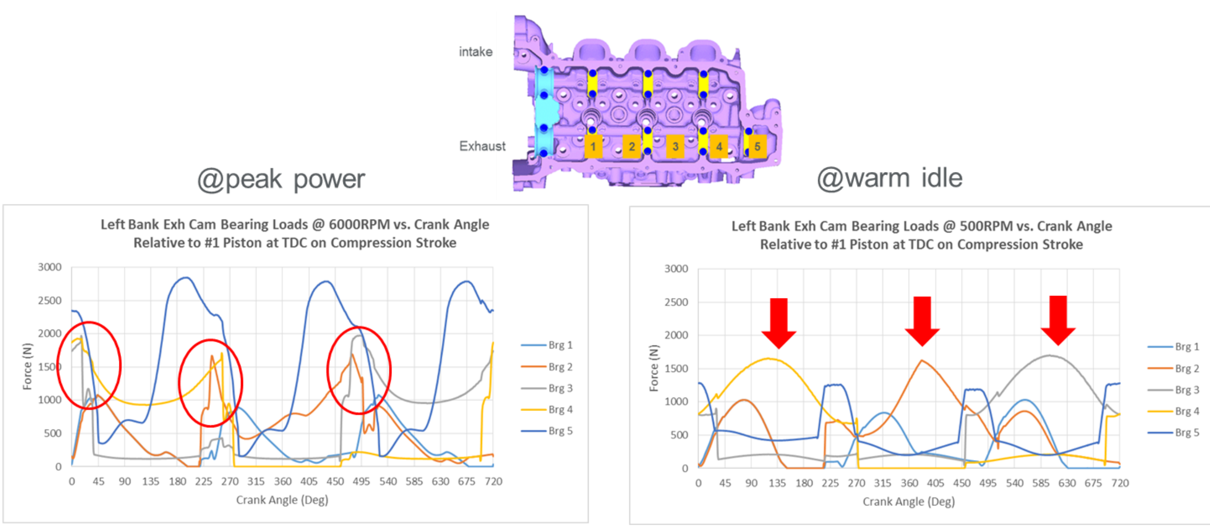

Figure 5: Left bank cylinder head exhaust side cam bearing and fuel pump load

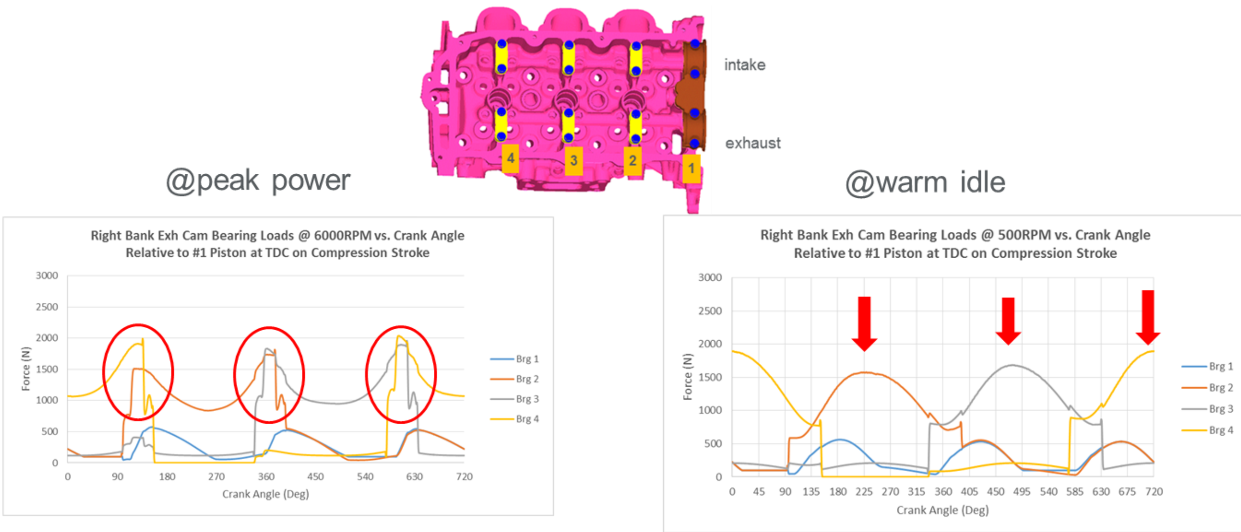

Figure 6: Right bank cylinder head exhaust side cam bearing and fuel pump load

4. CAM BORE DISTORTION AND MISALIGNMENT

Figure 7 illustrates how to calculate the cam bore misalignment for both adjacent and front-to-rear misalignments. Basically, from the full engine thermal structural analysis results, the cam bore distortion and hence the new deformed center for each bearing was calculated under different loading conditions. For adjacent misalignment calculation, say cam bearing 3 for example, it is the shortest distance from bearing 3 deformed center to the line connecting the two deformed centers of bearings 2 and 4. For front-to-rear cam bore misalignment, it is the maximum distance of the deform center from any one of the middle bearings to the line connecting the two deformed centers of the end bearings.

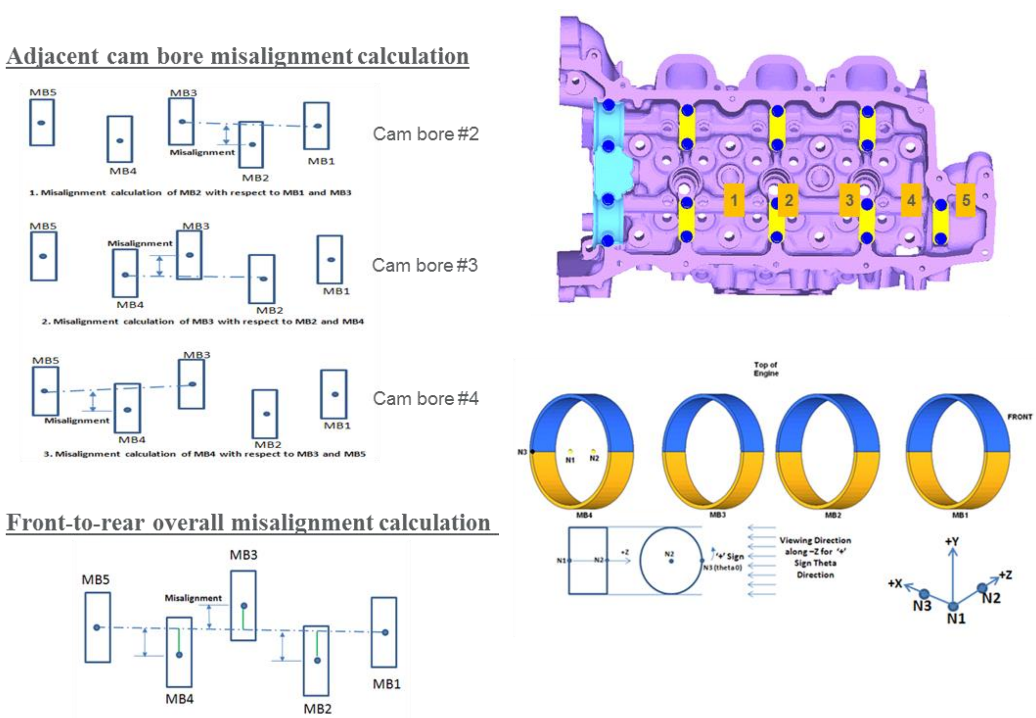

Figure 7: Cam bearing misalignment calculation

Figure 8 compares the adjacent cam bore misalignment between left bank and right bank cylinder head exhaust side cam bearing under different loading conditions. This is the average value of the adjacent misalignment for the middle cam bearings. The results indicated that maximum adjacent misalignment was observed at left bank exhaust cam under warm idle cam bearing load condition. It is the 'out-of-phase' cam bearing load at warm idle condition that caused individual cam bearing deformation more than the adjacent bearing(s) under specific cam rotation angle. The thermal load at warm idle does not contribute much on cam bore misalignment. The left bank exhaust cam under peak power cam load shows the 2nd highest cam bore adjacent alignment. This is because of the 'in-phase' cam bearing loading at peak power that caused multiple cam bearings deformed simultaneously, so the adjacent cam bore misalignment is not as significant as those calculated from the warm idle cam bearing load condition. It's also observed that the left bank exhaust cam bore misalignment is larger than the right bank exhaust cam. This is because the left bank head has five exhaust cam bearings while the right bank head only has four. The extra cam bearing makes the left bank cam tower support structure and camshaft more flexible due to longer length. As a result, the left bank cylinder head also show the highest front-to-rear cam bore misalignment at warm idle cam load bearing load condition, and it is much higher than the right bank cylinder head. This is illustrated in Figure 9.

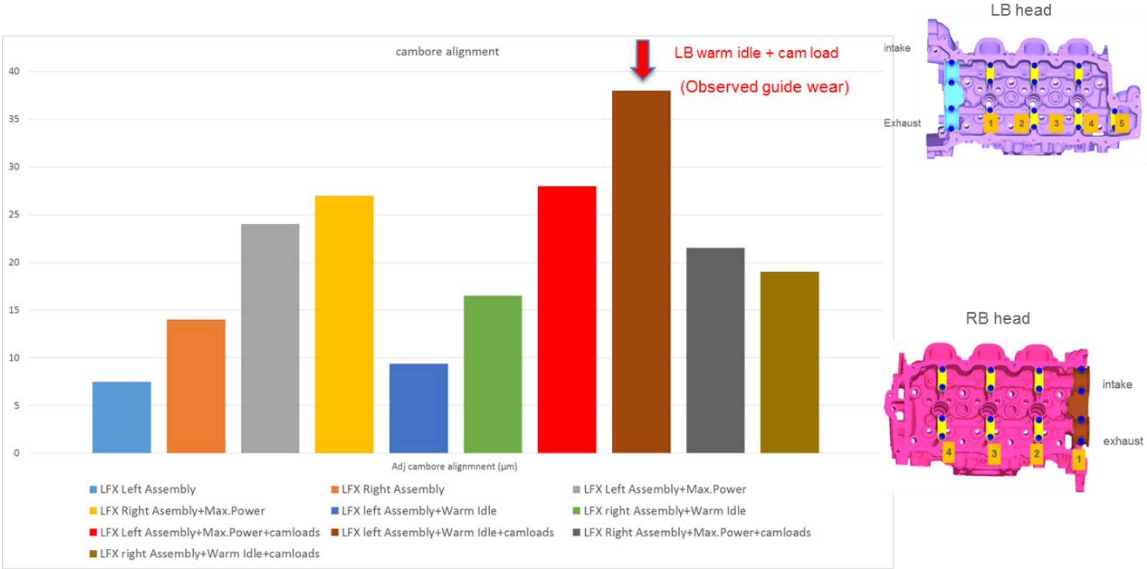

Figure 8: Cam bore adjacent misalignment under different loading conditions

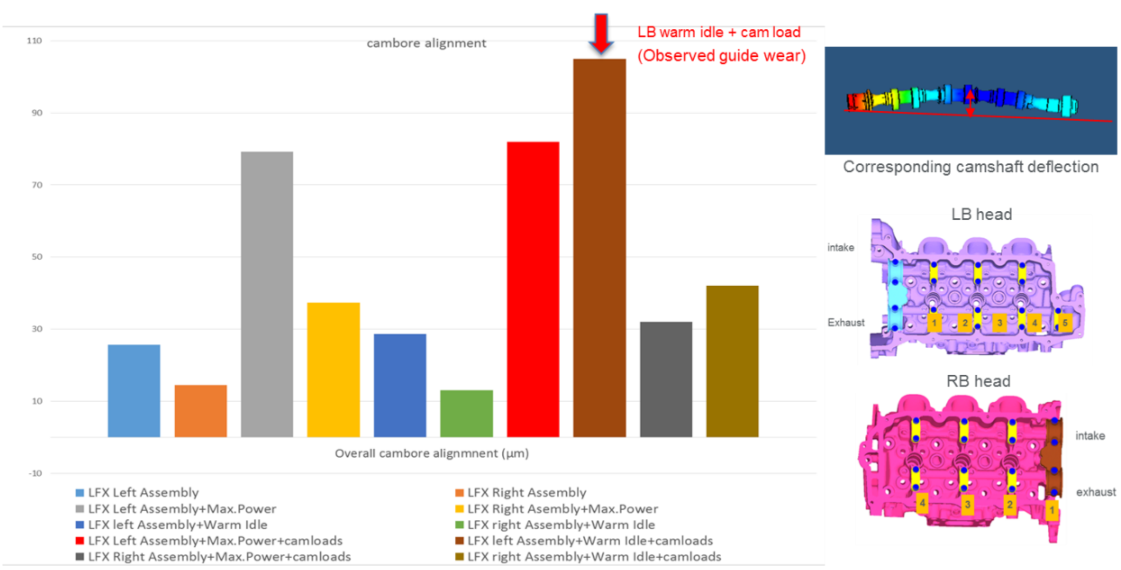

Figure 9: Cam bore front-to-rear misalignment under different loading conditions

5. VALVE TRAIN DYNAMIC ANALYSIS

The maximum adjacent cam bore misalignment**,** calculated at warm idle cam bearing loading condition as well as at peak power cam bearing loading condition**,** was used as input for the valve train dynamic analysis based on the model shown in Figure 4. In this study, the valve train dynamic model contains exhaust side middle cylinder structure of left bank cylinder head, exhaust valves, seats and guides, along with exhaust cam bearing 3. The two adjacent exhaust cam lobes, rocker arm, SHLA, valve spring and valve stem seal were also included in the model. The camshaft rotation in the valve train dynamic analysis was simulated based on both ideal cam axis and misaligned cam axis. In the latter case, the cam axis was rotated to match the maximum adjacent cam bore misalignment calculated from the full engine thermal structural analysis under different loading conditions for both left bank head and right bank cylinder heads.

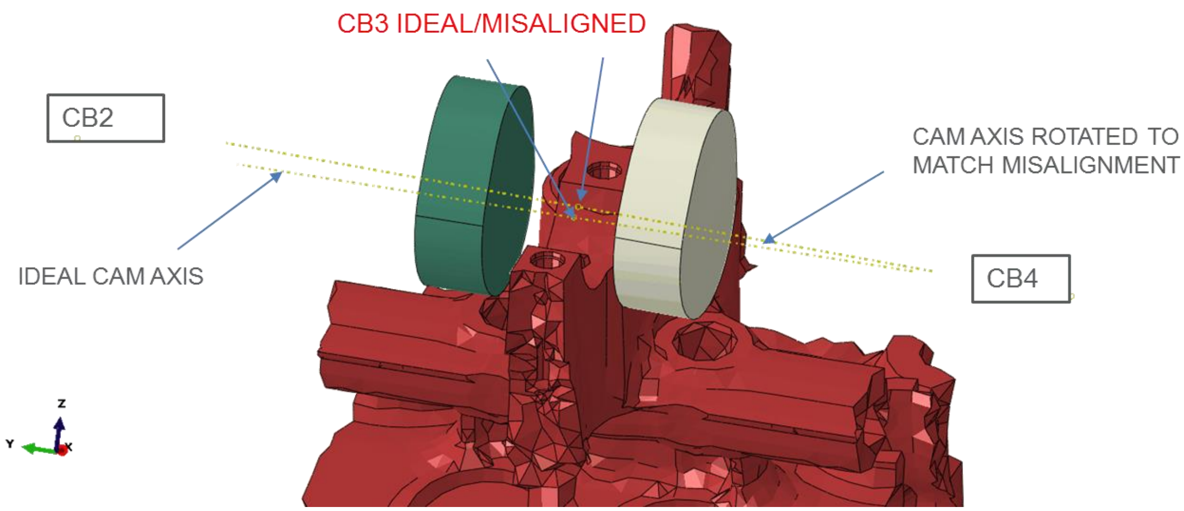

Figure 10: middle cam bearing ideal vs. misalignment cam axis rotation

In the dynamic analysis, Abaqus/Explicit was used to simulate the cam rotation. For the left bank cylinder head, the exhaust cam was rotated in the 'Reverse' direction (Clockwise looking from the front of engine) or 'Push me' rotation with respect to the SHLA as illustrated in Figure 1. For the right bank cylinder head, the exhaust cam was rotated in the 'Normal' direction (Counter-clockwise) or 'Pull me' rotation. The speed of the cam rotation was simulated based on the RPM corresponding to the warm idle as well as peak power operating conditions.

The output from the valve train dynamic analysis includes monitoring the contact between exhaust valve and guide, calculating the total contact force between exhaust valve and guide, and the contact between valve stem and exhaust rocker tang. These results were compared between warm idle and peak power engine running conditions, also between left bank head and right bank head exhaust valves, and correlated with guide wear observed from the experiment.

6. VALVE AND GUIDE CONTACT FORCE

Figure 11 compares the valve guide diameter (ID) measurement from a high mileage vehicle engine. The measurement was done at the top, middle and bottom of the valve guide for both left bank and right bank cylinder head intake and exhaust guides. The measured data indicated the wear happened mainly at the left bank exhaust valve guide along engine longitudinal direction and it was more severe near the top (combustion end) of the guide than at the bottom (camshaft end).

Figure 12 shows the total contact force along engine longitudinal direction between exhaust valve and guide vs. cam rotation angle under warm idle and peak power (GED) conditions, for both front and rear exhaust valves in the left bank cylinder head. The results indicated that larger contact force was observed between exhaust valve and guide at warm idle condition than the peak power condition for both valves. This matched well with the test data that showed guide wear only at low speed bench test (warm idle) that simulated the high mileage vehicle, but no evidence of guide wear on the high speed durability dyno test that mostly ran peak power engine operating condition. The larger contact force between exhaust valve and guide at warm idle versus peak power condition is related to the larger adjacent cam bore misalignment as discussed earlier.

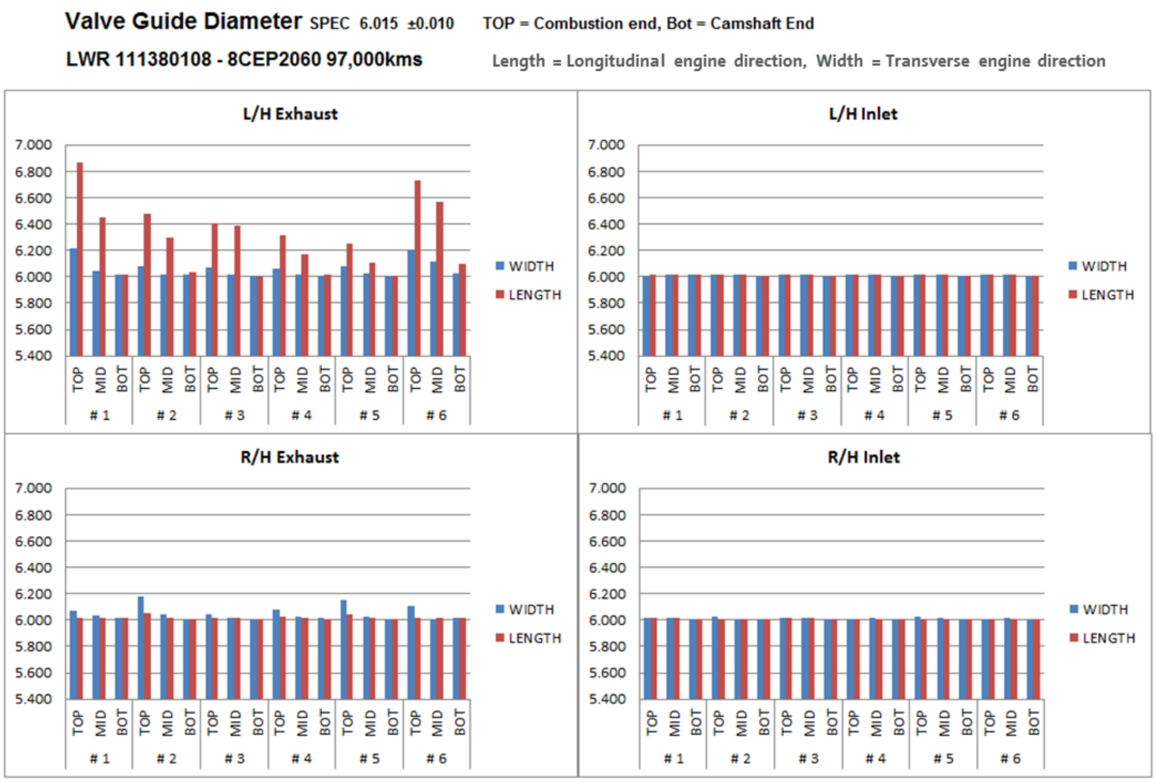

Figure 11: Exhaust valve guide diameter measurement from high mileage vehicle engine

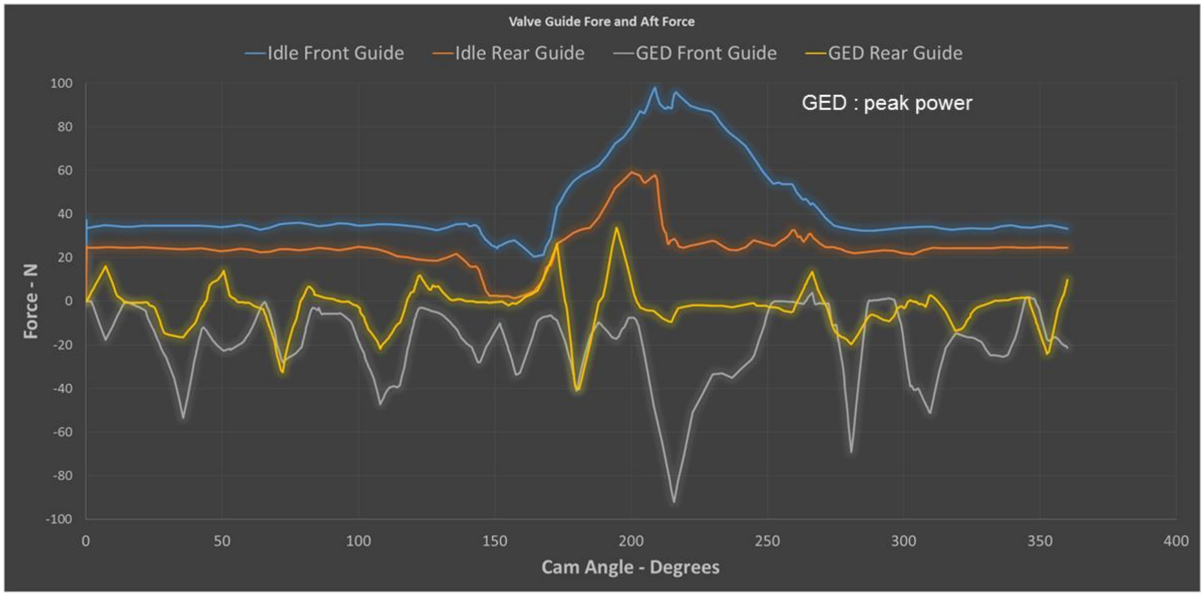

Figure 12: Left bank head exhaust valve and guide contact force under different loadings

Figure 13 compares total contact force along engine longitudinal direction between 'Reverse' cam rotation and 'Normal' cam rotations. The 'Reverse' rotation represents the exhaust cam 'Push me' (w.r.t SHLA) mechanics in the left bank cylinder head, and the 'Normal' rotation represents the exhaust cam 'Pull me' rotation in the right bank cylinder head. The results indicated that the 'Push me' type of cam rotation in the left bank head shows much higher contact force than the 'Pull me' type of cam rotation in the right bank cylinder head. This can explain why the guide wear was only observed on the left bank head exhaust valve, not on the right bank head.

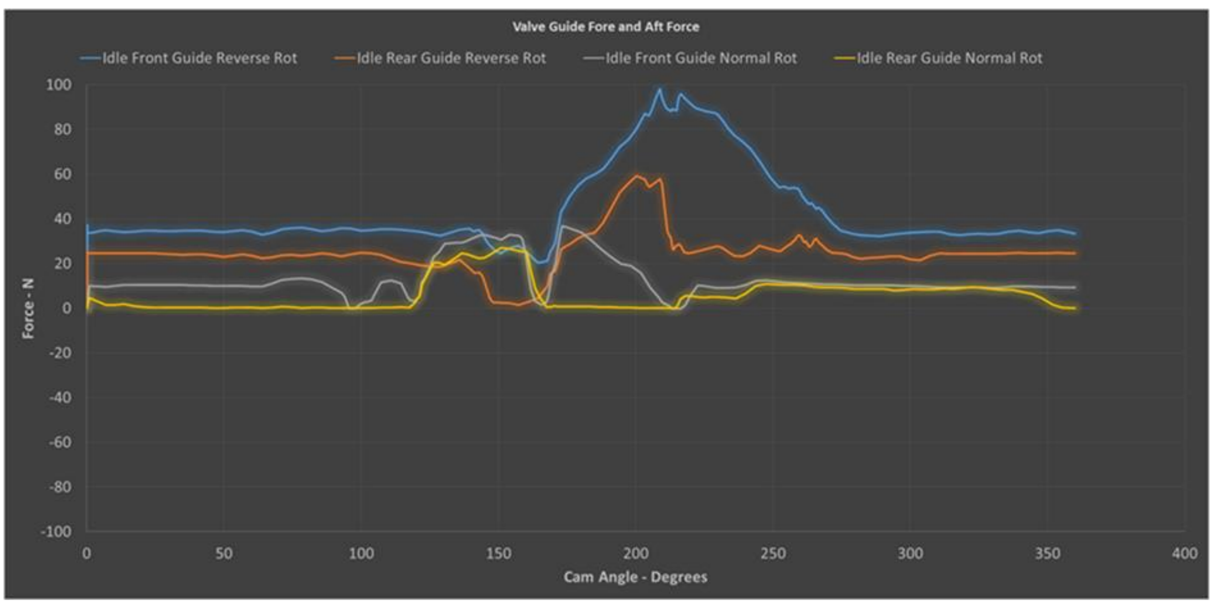

Figure 13: Exhaust valve and guide contact force between different cam rotation directions

Besides valve guide wear, there is also evidence of side contact at the tang of exhaust rocker in left bank cylinder head, but not on the right bank cylinder head exhaust rocker, from the high mileage vehicle engine. This is shown in Figure 14. Figure 15 compares the displacement of the exhaust rocker along engine longitudinal direction between the 'Reverse' rotation for left bank head exhaust cam and the 'Normal' rotation for right bank head exhaust cam.

The ‘Reverse’ rotation in the left head shows much larger displacement in exhaust rocker and therefore has higher tendency in contact with valve stem than the ‘Normal’ rotation in the right head.

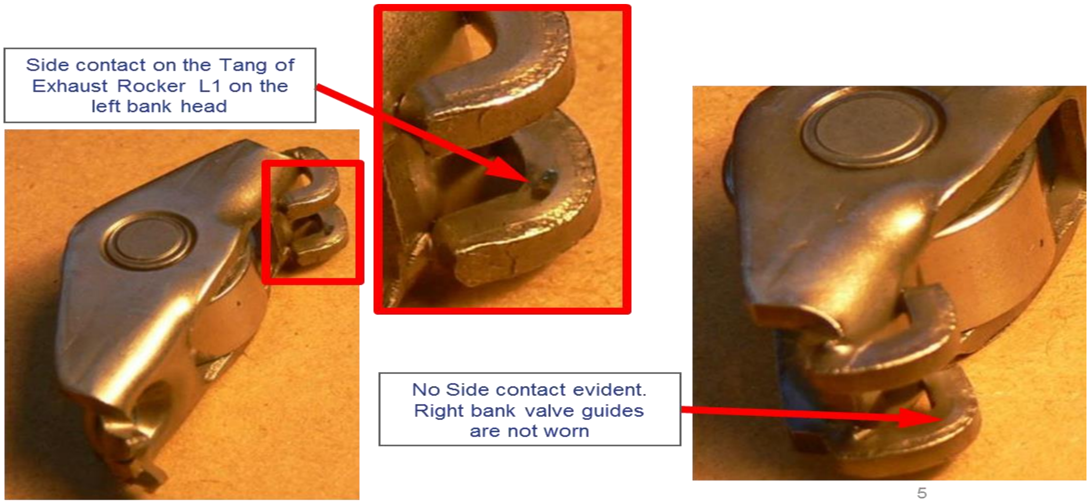

Figure 14: Side contact of exhaust rocker between left bank and right bank heads

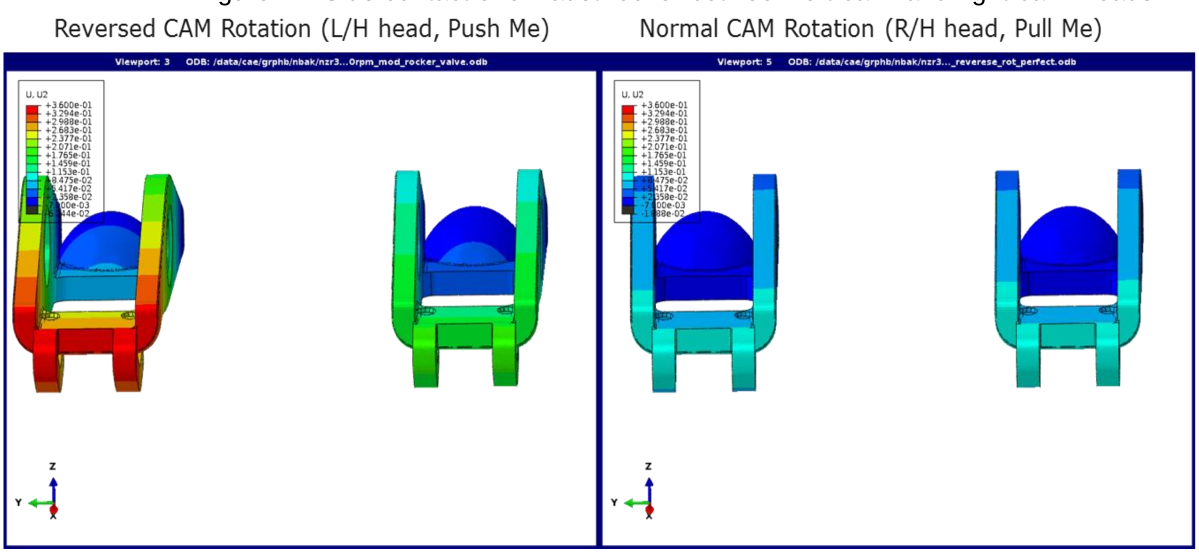

Figure 15: Exhaust rocker displacement along cam axis under warm idle condition

To understand why the ‘Reverse’ or the ‘Push me’ type of cam rotation caused side contact in exhaust rocker and exhaust valve guide wear, but not for the Normal or the ‘Pull me’ type of cam rotation, a free body diagram for the rocker side way movement was developed and illustrated in Figure 16. It indicated that when the camshaft spins in the ‘Reverse’ rotation that pushes the rocker towards the SHLA, the rocker moves along crank direction. Such motion will result in worse guide wear because of the larger longitudinal force result from the ‘self-correcting’ moment. On the other hand, when the camshaft spins in the ‘Normal’ rotation, the pull force away from SHLA results in lesser ‘self-correcting’ rocker motion.

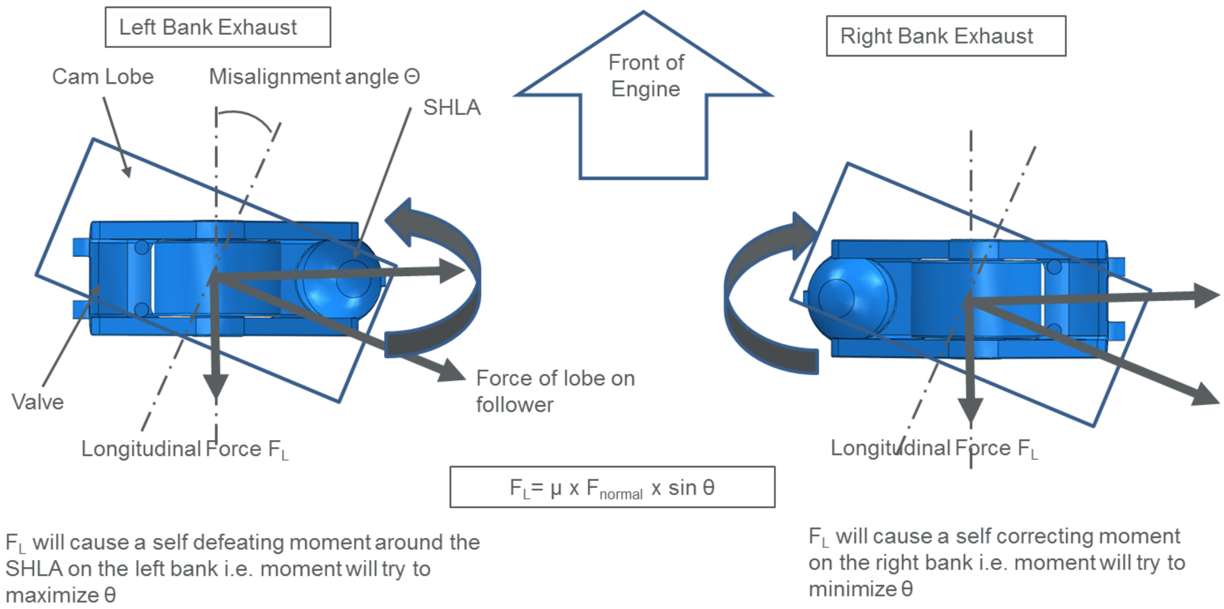

Figure 16: Free body diagram of exhaust rocker side way movement

7. GUIDE WEAR ANALYSIS

From the engine thermal structural analysis, the net clearance between valve and guide can be calculated based on the valve and guide thermal deformation. From the valve train dynamic analysis, the valve tip contact force can be calculated. These along with valve speed, valve lift distance, valve tilt moment are input to a Tribology model [1] that comprehends oil film lubrication effect in valve train dynamic analysis. This is illustrated in Figure 17. The wear of the valve guide can be calculated using Archard wear equation [2]

$$Q = \frac{KWL}{H}$$

Q : the total volume of material removed
K : a dimensionless constant
W: the total normal load
L : the sliding distance
H : the hardness of the softest contacting surfaces

The average oil film thickness and the maximum wear are compared between warm idle and peak power conditions, for both left bank and right bank heads in Figure 18. The results indicated that at idle condition, the left bank head exhaust valve guide shows higher wear rate than the right bank head. This was mainly due to the larger contact force between valve and guide along engine longitudinal direction resulting from the larger cam bore misalignment as well as the 'Push me' vs. 'Pull me' type of cam rotations. The results also showed the exhaust valve guide has larger wear at warm idle condition than at peak power. Besides the larger contact force as mentioned before, at warm idle condition the load mostly stays in one direction, but at peak power condition the load is oscillating, which results in larger oil damping effect, also allows oil to 'refill' oil that has been squeezed out, and reduces the wear. It is noted that in this wear study, oil was assumed to be fully flooded at the top of the valve stem seal and full oil lubrication between rocker arm and valve tip. However, at low speed condition, such assumption may not be valid due to weaker oil splash. In summary, the wear study showed that higher oil flow seal, longer valve guide, smaller clearance between valve and guide, and lower moment of inertia in valve train design helps to reduce the guide wear.

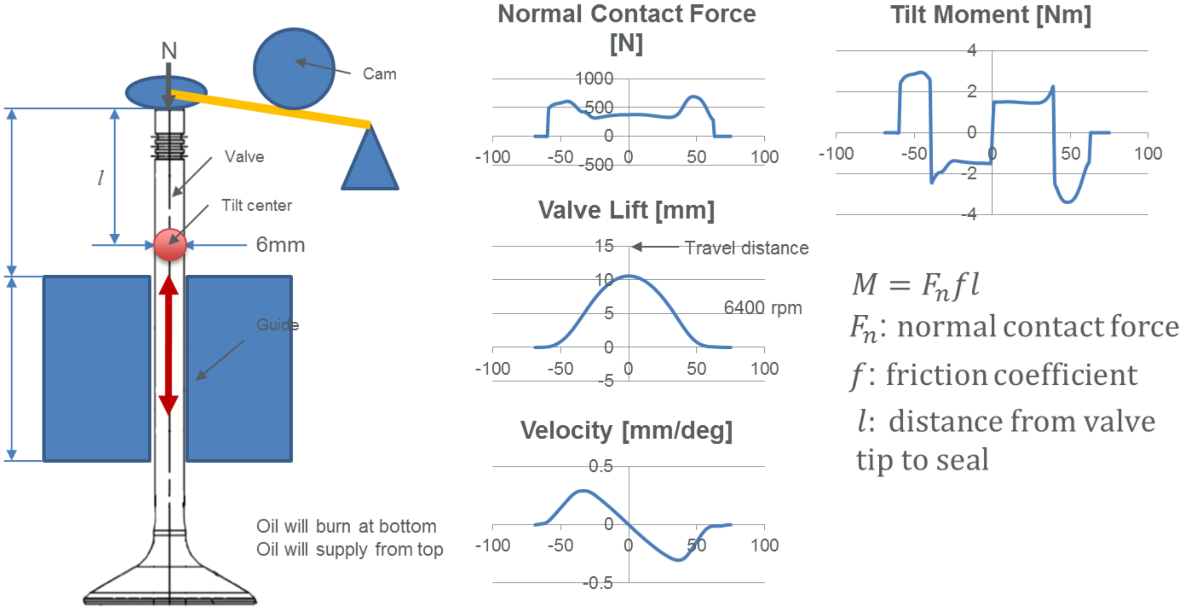

Figure 17: Valve train load and speed considered in Tribology model

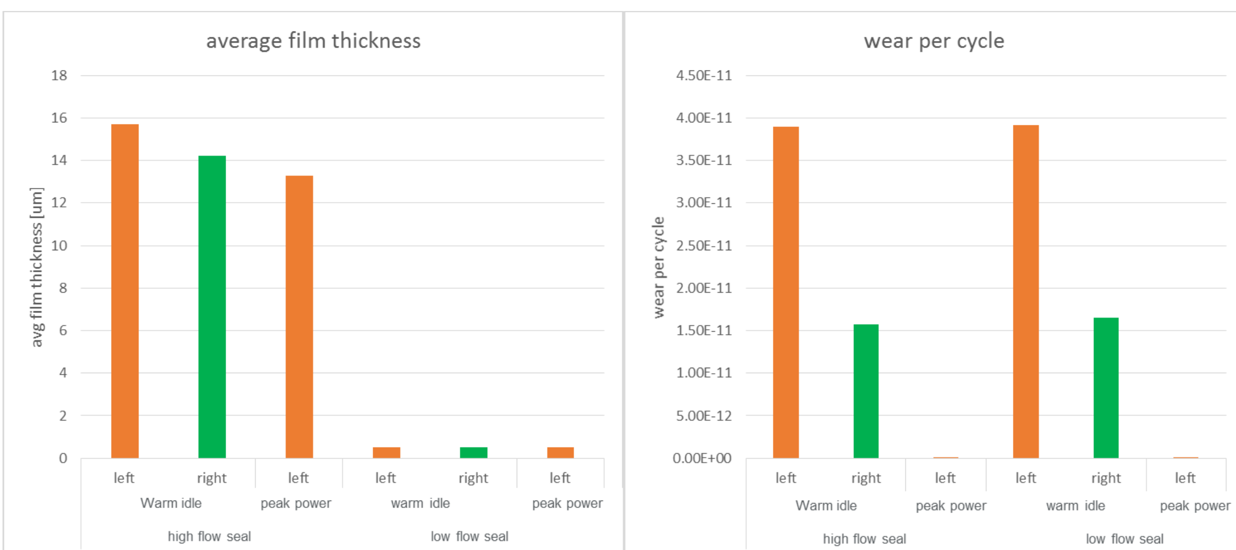

Figure 18: Average film thickness and maximum wear between valve and guide

8. CONCLUSIONS

An analytical model and process were developed to study the valve guide wear of automobile engine. The model used results, calculated from a full engine thermal structural analysis, as boundary condition for a valve train dynamic analysis based on a cylinder head submodel with valve train components. The results from both models were fed into a tribology model to calculate the valve guide wear.

The result from this study identified that the root cause of the exhaust valve guide wear in the left bank cylinder head from a high mileage vehicle engine was due to the large cam bore misalignment at warm idle condition. The study also proved the hypothesis that the 'Push me' type of cam rotation in the left bank cylinder head contributed to the exhaust valve guide wear. The larger cam bore misalignment at warm idle condition versus the peak power condition was resulting from the 'out-of-phase' cam load at lower speed which caused more relative deflection between cam bearings. The larger exhaust cam bore misalignment at the left bank head versus right bank head was due to the additional cam bearing and also could be due to the more flexible structure around the cam tower. The larger cam bore misalignment at exhaust side left bank head resulted in higher longitudinal contact force F_L between valve and guide and caused valve guide wear. Also, the longitudinal contact force F_L resulting from the Reversed cam rotation ('Push me') in the left bank head causes a moment around SHLA that would worsen with increasing cam misalignment and result in side contact at exhaust rocker, while F_L from the Normal cam rotation ('Pull me') in right bank head causes a moment that would correct the cam misalignment and result in no side contact at rocker. The wear index calculated based on thermal distortion and valve tip contact force from both models concluded that the left bank head exhaust valve guide had the highest wear rate per cycle at warm idle condition that agreed well with the testing data.

In this study, Abaqus/Standard was used in engine thermal structural analysis and Abaqus/Explicit was used for valve train dynamic analysis. Both solvers were running smoothly and were found effective in understanding the physics of the engineering issues.

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