

Effect of Valvetrain Components Misalignment on Valve and Guide Interactions in Automotive Engines

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ABSTRACT

Strict requirements for fuel economy and emissions are the main drivers for recent automotive engine downsizing and an increase of boosting technologies. For high power density engines, among other design challenges, valve and guide interactions are very important. Undesirable contact interactions may lead to poor fuel economy, engine noise, valve stem to valve guide seizure, and in a severe case, engine failure. In this paper, the valve stem and valve guide contact behavior is investigated using computational models for the camshaft drive in push and pull directions under several misalignment conditions for an engine with roller finger follower (RFF) valvetrain and overhead cam configuration. An engine assembly analysis with the appropriate assembly and thermal boundary conditions are first carried out using the finite element solver ABAQUS. Hot assembly displacements results for the exhaust valves, the guides, the valve seats and the cylinder head from the static analysis are then used as the boundary conditions for subsequent dynamic simulations of the valvetrain motion. A single RFF valvetrain is modeled using the elasto-hydrodynamically coupled multibody systems program FIRST by IST. A tolerance study is conducted to identify few key valvetrain misalignment conditions used in the simulations. The computational results show that at the given scale the influences on wear initiation at the bottom of the guide are very similar for the push and pull directions for the case with no misalignments, although the affected regions in the circumference of the guide differ. The results also show that the horizontal RFF misalignment with respect to the plane of RFF motion and with the drive in push direction has the most significant effect on wear initiation at the bottom of the guide. These results can be further processed for wear simulation for the valve guide. Simulation results for misalignments indicate that the wear pattern may vary significantly under various misalignment conditions.

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1. INTRODUCTION

Modern automotive engines face new design challenges to meet competing demands such as increased power, better fuel economy, tighter emissions control and reduced engine noise. These requirements are often addressed by downsizing the engine and employing boosting technology. The valvetrain system in a high power density engine needs to tackle several issues of which the valve and guide interaction is very important. The valve, the seat insert, and the guide wear due to undesirable contact interactions between the mating components can be a serious problem and thus needs proper assessment during the development of new engines.

Researchers attempted modelling of friction and valvetrain dynamics to improve the valvetrain design process. Calabretta et al. [1] used advanced mathematical models to quantify power loss at cam/tappet contact, tappet/bore contact and camshaft bearings for direct acting valvetrains. They have compared calculated and measured friction data for the valvetrain of a high speed passenger car engine as tested on a motored cylinder head test rig. Their results indicated that friction losses in a direct acting valvetrain are dominated by losses at the cam/tappet contact particularly at low engine speed. Tappet/bore interactions were less important but still worthy of consideration.

Lewis and Dwyer-Joyce [2] developed a semi-empirical wear model to account for wear mechanisms occurring at the valve/seat interface for predicting valve/seat recession based on the data gathered from laboratory simulation experiments. They have used an iterative software program RECESS to run the model. Blau [3] presented a mathematical model that portrays variations in the time-dependent removal and displacement of material from a diesel engine exhaust valve and seat combination. The model is based on the observation that the valves experience a combination of repetitive impact with slip. Blau [3] has used a high-temperature repetitive impact test system for basic tribology studies of the combined processes of mechanical wear plus oxidation at elevated temperatures. Boggupalli [4] investigated valve recession of a commercial vehicle engine inlet valve using the software tools IDEAS and TYCON for different valve seat angles. It should also be noted that misalignment of the valve causes the valve head/seat wear widths to increase at the point of contact that subsequently leads to a greater valve/seat wear at that location [2,4].

The above-mentioned researches are related to valve/seat recession issues and development of wear models for this contact pair. These works were mainly focused on the tribological aspects without

incorporating thermal distortions of the cylinder head or misalignment effects of the valvetrain system. Various misalignments that may arise due to tolerances in the valvetrain system in addition to thermal distortion of the cylinder head need to be studied thoroughly with appropriate modeling during an engine design phase, since investigating the valve or guide wear problems through multiple dynamometer tests would be costly.

In this paper, the valve stem and valve guide contact behavior is investigated for an engine with RFF valvetrain and overhead cam configuration. An advanced engine assembly analysis is conducted to simulate the assembly and thermal loads under a specified engine operating condition. The finite element solver ABAQUS is used for the static analysis. The hot assembly nodal displacements results for the exhaust valves, the guides, the seats and the cylinder head from this static analysis are then used as the boundary conditions for the dynamics simulations of valvetrain motion. A single RFF valvetrain is modeled for the dynamics simulation using the elasto-hydrodynamically (EHD) coupled multibody systems approach. The multibody systems simulations are conducted using the software program FIRST by IST. A tolerance study is conducted to identify few key valvetrain misalignment conditions. The computational models for the camshaft drive in push and pull directions under several misalignment conditions are analyzed. Results for selected misalignments are then presented and compared with that of the case with no misalignments to identify the major influence. Finally, some conclusions based on the results of these investigations are made.

2. MODELING

Computational models consist of two parts to investigate the valve and guide interactions – a static engine assembly simulation and a single valvetrain based multibody system dynamics simulation. A schematic of the simulation steps is shown in [Figure 1](#). Brief descriptions of the models are as follows.

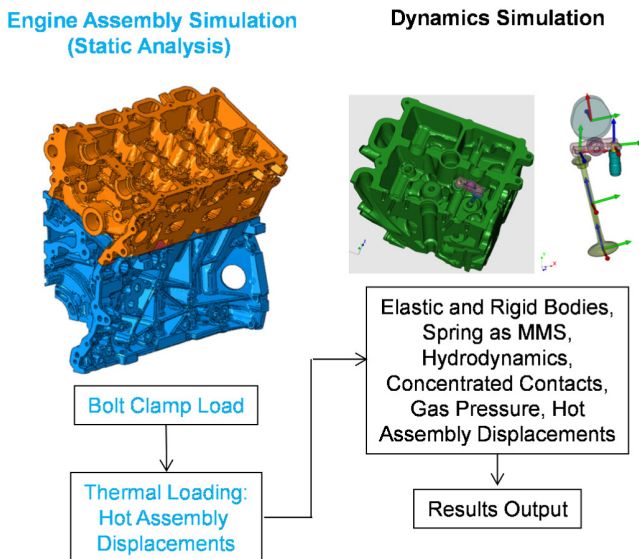


Figure 1. A schematic of the simulation steps.

2.1 Engine Assembly Simulation

An advanced engine assembly analysis of a V6 engine is conducted using the finite element solver ABAQUS. The valves, guides, and seats are meshed with linear hexahedral elements with a fine mesh

size that is acceptable for direct use in dynamic simulations as discussed later. The rest of the other components in the engine assembly are meshed with quadratic tetrahedral elements. In this static structural analysis, the press fit of the valve seats and the valve guides is simulated. The cylinder head, cylinder block and cylinder head gasket are assembled with the specified bolt load to simulate the cylinder head deformation under assembly load at room temperature.

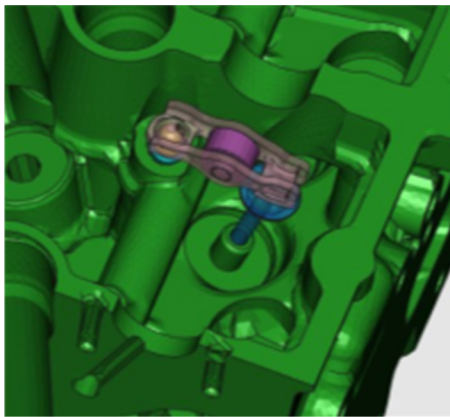
An appropriate thermal loading corresponding to a particular engine operating condition is applied after the engine assembly simulation [5]. The hot assembly condition is important as it impacts the global deformation of the port wall, valve guide, and seat and the local deformation of the press-fitted guide and the seat due to thermal expansion mismatch of dissimilar metals. In this study the hot thermal distortion is corresponding to peak power engine speed and is considered as a given condition under the operating thermal load.

2.2 Dynamics Simulation

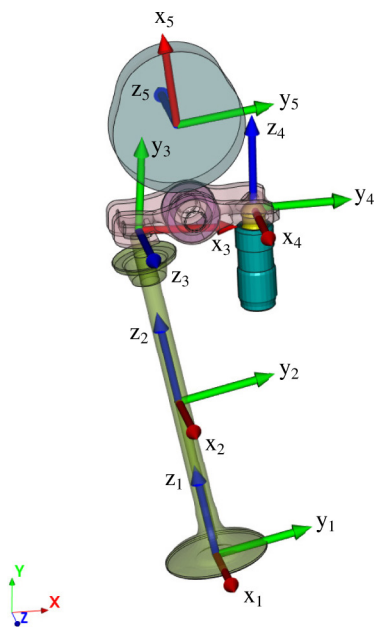
The exhaust valves and the guides at the bottom of the valve guide location tend to be about four to five times hotter than that of the intake sides and hence the exhaust valve of the V6 engine is selected for this study [6]. A single valvetrain based submodeling approach is adopted in this paper for computational efficiency. The analysis scheme presented here can be applied to any valve. The single valvetrain based multibody system dynamics model consists of an overhead cam configuration using a rolling contact cam follower, a hydraulic lash adjuster (HLA), and a valve with a single spring. The cam is assumed to be rigid. The lever and the roller of the RFF are assumed to be elastic and rigid, respectively. The plunger and the housing of the HLA are modeled as rigid bodies. A suitable section of the cylinder head, the valve, the seat and the guide are modelled as elastic bodies. The valve spring is modeled using a multi-mass-spring (MMS) model. The needle roller bearing of the RFF is solved using characteristic data and the roller bearing module by the manufacturer, Schaeffler Technologies. The elastic cylinder head section is fixed on the mating surface to create realistic elastic deformations of the areas affecting the single valvetrain included in the model. Cylinder pressure corresponding to the operating condition is applied at the combustion chamber surface. Pressures at the combustion chamber and exhaust port channel are applied on the exhaust valve head surfaces with opposite sign. Since the other valves were not modeled the resulting force due to cylinder and port pressure on each individual valve head is directly applied to the corresponding seating surface.

The simulation solves Newton's equations of motion in the time domain, with all bearings and other kinematic restrictions being modeled as force couplings. All rigid bodies are described through center of gravity, complete tensor of inertia and mass. For elastic bodies a reduction of order is performed. The reduction step combines static and modal analysis to reduce the dimension of the model by several orders of magnitude without compromising the static and the dynamic responses of the model in the areas of interest, e.g. the valve guide, the valve seat. For these areas of interest the main degrees of freedom (main-DOF) are defined as unit deflections of nodes or groups of nodes. The result of a static analysis for each unit deflection of a main-DOF represents a shape vector, which belongs to the deflected main-DOF. In addition a set of modal

Ritz- vectors is determined by an eigenvalue analysis of the model for the fixed main-DOFs and the boundaries. The static and modal Ritz- Vectors are combined into a transformation matrix to reduce the order of the original FEM-model for the elastic structure.



a.



b.

Figure 2. (a) Section of the cylinder head and (b) a single exhaust valvetrain model.

The calculation of the hydrodynamic pressure distribution for the journal sliding bearings is realized by solving the Reynolds equation at every time step. In the mixed lubrication regime, the hydrodynamic pressure is superposed by the contact pressure based on surface roughness. Crowning, local contours or shapes and the elastic deformations of the bearing surfaces for the valve, the valve seat and the guide are considered for the calculation of hydrodynamic gap functions. For the consideration of the surface roughness effects, the stochastic model by Greenwood and Tripp is applied using the standard deviation of the surface roughness. Thermal distortion and rigid translation and rotation of the exhaust valve stem and guide due to hot assembly condition of the cylinder head are included in the model. Rigid-body translations and rotations of the valve seat due to

thermal distortion of the cylinder head are also included. The averaged rigid body translations of the valve, the guide and the seat due to hot assembly displacements have been subtracted to prevent any artificial misalignments between the RFF, the valve, the guide and the seat. This also ensures that the relative positions of the valve stem to the guide, and the valve head to the seat are intact.

Figures 2(a) and 2(b) shows a portion of the cylinder head and the single exhaust valvetrain model, respectively. There are multiple local coordinate systems marked in Figure 2(b) and these are major coordinates for force couplings in the model. Usually local z-axis is defined as axis of rotation for the cam and roller, and axial movement for the valve and HLA. All results output presented in this paper are based on these local coordinates and will be indicated appropriately. The global z-axis is parallel to the longitudinal axis of the engine. Note that the local axes color representations are similar to that of the global axes color.

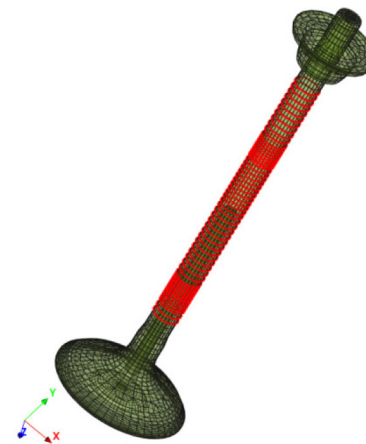


Figure 3. Contact zone for EHD simulation between the valve and guide shown with red nodes.

Figure 3 shows the contact zone marked by red nodes for EHD simulation between the valve and guide. EHD models are used for the valve, the guide, and the seat. Standard roughness values are used for the valve guide, the valve stem, the guide inner, the valve head, and the valve seat surfaces. A nominal clearance between the exhaust valve stem and the exhaust guide is used. The variation of clearance between the exhaust valve stem and the exhaust guide can further be studied at hot assembly condition to identify other worse conditions and is excluded in this misalignment study. For example, there are variations of other parameters such as valve guide pressfit, thermal expansion coefficients of the valve stem, the guide and the cylinder head materials, etc. might influence the worse condition. This study is mainly focused on the misalignment effect of the cam and RFF interactions. Only the upper half of the valve guide is considered to be filled with oil. Oil film thickness in the lower half of the valve guide is reduced to 0.5 microns. A fully filled bearing with the viscosity of air is used for the valve seat simulation, since only contact pressures and friction are of interest, although a thin film thickness could alternatively be used. Appropriate friction coefficients are used for all contacts in this investigation for the comparative study. However, it should be noted that the coefficient of friction depends on several other factors and any such dependency is not considered in this study due to insufficient data.

2.3 Definition of Misalignment

Valve/seat misalignment, valve/guide or guide/seat concentricity issues may arise from thermal distortion of the cylinder head, the valve seat and the guide, tolerances of components or dynamics loadings. These can impact the smooth operation of the valvetrain system. Investigating all these misalignments in detail at the same time could be computationally quite challenging. This study is focused on investigating the effect of tolerances of components especially between the RFF roller axis to the cam base circle axis. This is particularly important since the RFF is driven by the cam and so any misalignment between these two components needs to be studied for robustness purposes.

A tolerance study is carried out to predict angular variability of the exhaust RFF roller axis to the camshaft axis. The details of the tolerance study are out of scope of this paper. Based on the tolerance study three key misalignment conditions, identified as Misalignment 1, Misalignment 2 and Misalignment 3, are used for simulations. These misalignments are analyzed separately to understand the extent of effect of each of the misalignments on the valve and guide interactions. Misalignment 1 is the distance between the roller and cam centers as shown in Figure 4(a). In the simulation the cam center is moved towards to the HLA by a distance of Misalignment 1. Figure 4(b) shows Misalignment 2 is an angle between the cam and the roller axes. In the simulation the camshaft axis is rotated as shown by the dotted line in Figure 4(b) so that the included angle between the cam lobe and the RFF roller is Misalignment 2. Figure 4(c) shows Misalignment 3 is an angle between the RFF plane and the cam lobe plane. Misalignment 3 is modeled as a dislocation of HLA with respect to the valve center line, such that the RFF sitting with pad centered on the valve shows an angle towards the rear of the engine relative to the cam as shown in Figure 4(c). Note that the actual misalignment values used in the simulations are the maximum values obtained from the tolerance study.

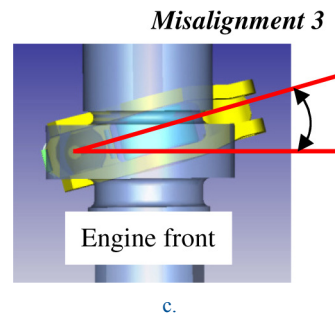
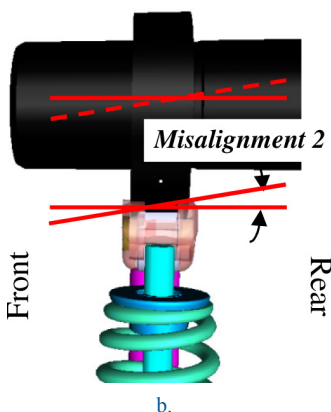
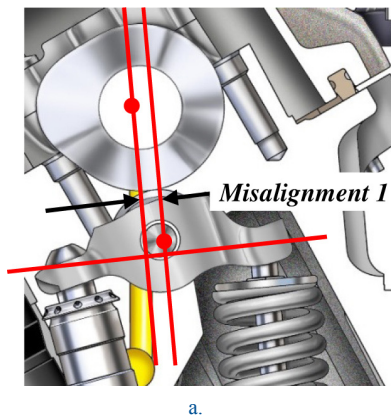


Figure 4. Based on a tolerance study three key misalignment conditions are identified as Misalignment 1, Misalignment 2 and Misalignment 3. (a) Misalignment 1 is the distance between the roller and cam centers. (b) Misalignment 2 is an angle between the cam and the roller axes. (c) Misalignment 3 is an angle between the RFF plane and the cam lobe plane.

2.4 Boundary Conditions and Data

The following data and boundary conditions are obtained to prepare the dynamics simulation model. The three dimensional geometry model based volume definitions of the RFF, the HLA plunger and body, valve with the spring retainer, the appropriate cylinder head section, the valve seat and the guide are used to create rigid and elastic bodies as mentioned before. Geometry and stiffness of the valve spring is obtained for spring modeling. Contour profile for the cam is directly used in the simulation for better accuracy. Appropriate elastic material properties such as Young's Modulus, density and Poisson's ratio are used for the components modelled as elastic bodies. A nominal clearance is used for all lubricated surfaces. Surface roughness information for all manufactured surface contours in contacts and bearings are obtained from manufacturing specifications [6]. In this investigation the thermal distortion corresponds to the peak power engine speed, which is 5750 RPM. Dynamic viscosity of oil at hot condition and gas pressure acting on the valve at peak power engine speed are also used in the simulation.

Table 1. Simulation cases.

Cam rotation w.r.t. the RFF	Case			
	Base	Misalignment 1	Misalignment 2	Misalignment 3
Push	Base	Misalignment 1	Misalignment 2	Misalignment 3
Pull	Base	Misalignment 1	Misalignment 2	Misalignment 3

2.5 Considered Factors

Dynamics of the valve train including lash adjuster hydraulics and spring mass effects are considered in the simulation. Local deformation of the valve and the guide are included to accurately model the interaction behavior under a particular engine speed. Elasticity of the valve, the valve guide and the seat are important to obtain representative contact pressure distribution. Contact pressure distribution in valve seat and line contacts with surface contours are considered for both nominal and misalignment cases. Wear indicators