

Compression-Release Engine Brake Modeling and Braking Performance Simulation

Peirong Jia and Qianfan (Harry) Xin
Navistar, Inc.

ABSTRACT

A diesel engine multi-cylinder valvetrain model including a hydraulic engine braking system was developed. The model can be used for valvetrain dynamics analysis in both engine firing and braking conditions. Moreover, it can be used to investigate engine braking performance with conjugated analysis by combining the valvetrain model with an engine thermodynamic cycle simulation model. Dynamic valve lift profiles, which are important for accurate engine performance simulations, can be simulated with the model, including valve floating prediction for each cylinder during engine braking. The valvetrain model was used in the design of a diesel engine brake system and in the analysis of engine braking performance at the sea level and different high altitude and ambient temperature conditions. Valvetrain dynamics and the impact of EGR (exhaust gas recirculation) valve leakage or opening on engine braking performance were also evaluated.

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1. INTRODUCTION

Compression-release engine brakes [1, 2, 3] (also called compression brakes) are often required for heavy vehicle driving operation during retarding to slow down the vehicle or hold an acceptable speed on downgrades. Compression brakes have been developed as a part of engine hardware in heavy-duty diesel engines and their designs are closely related to the valvetrain and the cylinder head. Compression brakes generate retarding power mainly by producing net negative power during the compression stroke and the expansion stroke of a four-stroke engine during non-fueling braking conditions, and also by producing certain pumping loss during the intake and exhaust strokes. When the compression-release brake system is activated, the exhaust valve(s) are opened at a small lift height near the TDC at the end of the compression stroke so that the compressed air charge in the cylinder is suddenly released out of the cylinder, and the cylinder pressure is quickly reduced in order to avoid generating significant positive power during the expansion stroke. For turbocharged diesel engines using braking gas recirculation (BGR) [1, 4], opening the exhaust valve(s) during the late portion of the intake stroke with a secondary exhaust valve lift allows the high pressure in the exhaust manifold to drive certain high-temperature gas charge to flow back from the exhaust manifold into the cylinder in order to further increase retarding power. Engine brake system modeling [5,6,7], engine brake designs using

variable valve actuation (VVA) [8, 9], the impact of design and calibration parameters on engine braking performance [9], engine braking performance simulation at various environmental conditions [10], and braking system assembly designs [11] are important topics in the design of advanced engine brake systems. Some modeling techniques of engine brake performance were introduced by other researchers [5]. However, advanced integrated modeling techniques for accurately simulating both engine braking thermodynamic performance and valvetrain dynamics are still generally lacking in the literature. With advanced simulation tools and methodologies, more insights into the details of engine braking events can be revealed; dynamic motions of the valves can be investigated; the engine and valvetrain behavior of multi-cylinder braking systems can be captured in high fidelity; innovative engine brake concepts can be developed; braking cam profile design and optimization can be conducted in order to achieve a given target of retarding power; and engine cycle performance during retarding at different ambient temperature and altitude conditions can be analytically studied to examine various performance parameters and durability-related engine system parameters. This paper develops a comprehensive modeling technique and methodology for integrated engine performance and valvetrain dynamics during engine braking operation.

A diesel engine valvetrain model including a hydraulic engine braking system was developed in this study with

advanced features of a commercial software package GT-VTRAIN [12]. An engine cycle performance simulation model for firing and retarding was developed with GT-POWER [12]. Dynamic valve lift profiles, which are important for accurate engine performance simulations, were simulated with an integrated (conjugated) model that considers valve motions, gas pressure loading effects on the valvetrain, their impact on engine cycle performance and in turn on gas loading, valvetrain dynamics phenomena such as valve floating off the valve seat, and hydraulic braking dynamics, etc. For modern diesel engines using EGR, the EGR valve is usually fully closed during engine braking in order to increase pumping loss and retarding power. However, EGR valve opening can be used as an engine calibration parameter to regulate braking performance parameters in order to meet all the performance objectives and durability design constraints. The impact of EGR valve leakage or opening on engine braking performance was also studied. Section 2 introduces model development of the valvetrain that includes a hydraulic system in the engine brake. Section 3 presents the effects of cam profile designs on engine braking performance. Section 4 presents valve floating prediction and engine braking performance analyses at full and partial braking operations at different altitude and ambient temperature conditions.

2. MODELING OF VALVETRAIN WITH HYDRAULIC BRAKING SYSTEM

Valvetrain System

Figure 1 shows a schematic diagram of an overhead valvetrain incorporating an engine brake system using a hydraulic fluid supply passage for a six-cylinder diesel engine. There are three cam lobes for each cylinder: intake, exhaust, and braking. All the cams share a common camshaft. Unlike the intake cam or the exhaust cam that has only one cam profile for an intake or exhaust event, each engine braking cam has one compression-release cam profile (near the end of compression stroke) and a BGR secondary exhaust valve lift profile (in the late stage of the intake stroke). The braking cam lobe connects to a hydraulic braking system through a braking cam roller and a socket-pushrod mechanism. A lost motion follower, along with its spring, as a part of the valvetrain braking system, absorbs and releases energy of the rotating braking rocker arm during both firing and braking operations. Note that the intake cam, the exhaust cam, and the intake valves are not shown in Fig. 1. The cam-side braking rocker arm connects to a master piston through a plunger link. The master piston is actuated via a socket-

pushrod connection (equivalent to a crank-slider mechanism) on the cam side of the braking rocker arm. A hydraulic circuit connects the master cylinder and the slave cylinder. A slave piston rod may contact the valve-side exhaust rocker arm (there is lash between them). The rotating motion of the braking cam lobe is converted to the motion of a braking cam follower in either firing or braking condition. During engine firing conditions, a check valve in the hydraulic passage is opened so that the oil pressure in the hydraulic circuit is not high enough to overcome the slave piston's spring force to push the slave piston rod to move. While in engine braking operations, the hydraulic circuit is filled with pressurized oil and the check valve is closed. The rotating motion of the braking cam is converted to the translating motion of the slave piston rod, through a master-slave cylinder hydraulic system, which pushes the exhaust rocker arm to rotate about its pivot center and open the exhaust valve(s) through a valve bridge. Figure 2 illustrates cross-sectional diagrams of the exhaust and braking valvetrains.

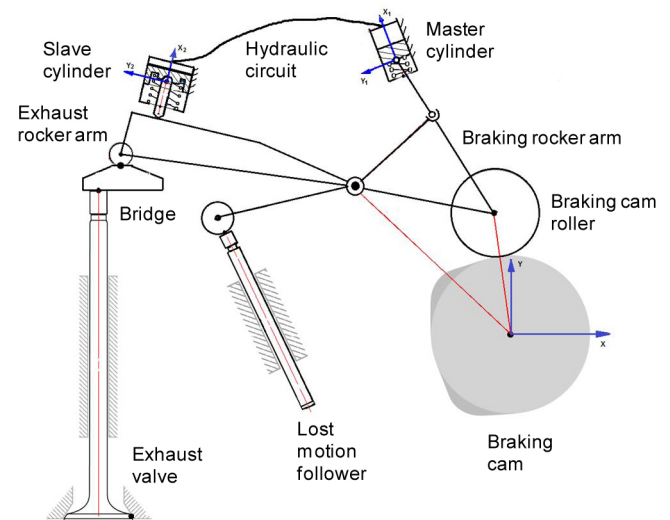


Figure 1. Schematic diagram of the valvetrain with the hydraulic braking system.

2.2. Single-Cylinder Valvetrain Modeling

If the hydraulic circuit, master cylinders, and slave cylinders are ignored, the valvetrain is actually as a conventional mechanical valvetrain system. It can be modeled with GT-VTRAIN with an implicit method [12] when all the input data such as valvetrain geometry, cam profiles, and material properties are known. The advantage of the implicit modeling is that valvetrain kinematic and Quasi-Dynamic Analysis (QDA, [12]) results can be retained. However, the valvetrain in this paper is a special system that



The details of the modeling of the master/slave cylinders and pistons and the hydraulic circuit are briefly described as follows. The linkage consisting of a master cylinder, a master piston, a connecting plunger, and a cam-side braking rocker arm is essentially a crank-slider mechanism, which is driven by the braking rocker arm. The master/slave pistons, the master/slave piston connecting plunger and rod, and the plunger and rod connection parts on the braking rocker arm and the exhaust rocker arm are defined as rigid parts having inertias. The master/slave piston pin contact locations on the braking rocker arm and the exhaust rocker arm are rigidly connected to the corresponding rocker arms. The master piston plunger and the braking rocker arm are modeled as a ball-to-socket contact. Both the master and slave pistons have springs inside the cylinders, with the master cylinder having a helical spring and the slave cylinder having two helical springs. Figure 4 shows the output diagrams of the dynamic simulation of the valvetrain.

A multi-cylinder valvetrain model was built by linking several identical single-cylinder valvetrain models together and aligning them on the same camshaft. Cam timing of each cam lobe was properly defined, and the gas loading acting on the valves for each cylinder was applied according to the engine firing order by taking the output data of cylinder pressures and port pressures from engine thermodynamic cycle performance simulation. [Figure 5](#) shows the coordinate system of the multi-cylinder valvetrain. The origin of the coordinates system was selected at the center of the first bearing. The “Z” coordinate of each cam lobe's center relative to the origin was calculated by using the engine and camshaft geometry information.

