Tribological Processes in the Valve Train Systems with Lightweight Valves

New Research and Modeling

Krzysztof Jan Siczek

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Preface

Nowadays the goal of achieving the best engine performance and lowest fuel consumption and emissions drives the development of all engine assemblies. Because the valve train operation influences all these aspects, its development is of crucial importance.

Valve trains in modern engines operate in complex conditions that change both from cycle to cycle and long term. Proper recognition of them should take into account not only courses of loading, temperature, and lubrication conditions during the operating cycle but also wear and friction for all mating elements. The introduction of new materials also changes the tribological properties for mating surfaces.

Although there are many excellent articles and books about valve train design, the effects of wear and friction of all valve train components on its operation as a whole are rarely taken into account. Because modeling and control of valve trains have played key roles in the technical development of all assemblies in modern combustion engines, I decided to write this book.

The material assembled in this book represents my work during the past decade on engine valve train research and development at Lodz University of Technology in Poland. This book is intended to provide a better understanding of engine valve trains by presenting the major aspects of valve train modeling, control, simulation, and design.

This book consists of 11 chapters. Chapter 1 describes different solutions for obtaining increased fuel economy and lower emissions, including variable valve control, exhaust gas recirculation, direct injection, and hybridization of vehicles. The approximate criterion for classifying valves as lightweight is also presented.

Chapter 2 describes the principles of valve train operation. These include engine types, lead, lag, overlap, scavenging, rotary port system, poppet valves arrangement, variable valve actuation, variable valve timing, and cylinder and valve deactivation.

Chapter 3 presents the different spark-ignition engine valve trains. They can use camshaft phaser, adjustable timing, stepwise adjustable valve lifts, or stepless adjustable valve lifts.

Chapter 4 discusses the different compression-ignition engine valve trains, including compression-ignition engine valve timing control, systems of direct action, hydraulic systems of "lost lift," profile generation systems, and variable speed systems.

Chapter 5 presents valve train thermodynamic effects and describes valve opening strategy, valve closing strategy, exhaust gas recirculation, cam phasing, cold-start valve phasing, the role of valve overlap, valve stroke, effective compression ratio, exhaust temperature, and turbocharging.

Chapter 6 discusses the valve train kinetic effects. It is especially considers valve train operating conditions, valve rotation, seat insert - guide misalignment, cam profile, forces loading valve train, valve train stiffness, valve spring, lash adjuster, friction phenomena in valve train nodes, tribological quality criteria and quality indicators.

Chapter 7 addresses the valve train tribology. In particular, the term "tribology" is explained. The chapter also discusses the tribological phenomena, friction models and compensation, lubrication, wear intensity, and models and the role of pollutants.

Chapter 8 discusses the mechanical component design and analysis. It discusses the materials, design, and analysis methods for the valve train drive system, including gear, chain, and cogged belt drives for camshafts; valve springs; and small parts in the valve train, including spring accessories, rocker arms and cam followers, lifters, pushrods, and valve lash adjustment elements. Different aspects of the classical and lightweight valves, guides, and seat inserts are also presented.

Chapter 9 elaborates on the advanced mechanical valve train design and analysis. It presents solutions for obtaining variable valve stroke by switching the cam profile. It also discusses systems with continuous change of valve stroke, variable valve lift, and variable control of the valves via the camshaft. In addition, it provides a review of the cam valve drives.

Chapter 10 is concerned with the future of valve train systems. Camless drives (electromagnetic, electromechanic, electrohydraulic, and electropneumatic) are presented, and the role of valve settling speed is discussed.

Finally, Chapter 11 discusses research on valve trains, including testing methods, testers for valve trains, computer simulations, and the role of sum of media flows. It also presents a simplified simulation algorithm.

This book was written as an engineering reference book on the analysis and modeling of valve trains with lightweight valves. It can be useful for training courses on valve train development and design. It should enable design engineers to understand valve train control algorithm design and development. It can be useful for both undergraduate- and graduate-level valve train modeling and design courses. I hope that this book will succeed in helping the reader understand this interesting technology.

I thank my colleague or, better, my mentor Krzysztof Zbierski, PhD. Eng., for his excellent cooperation and help during my research. I also thank my colleagues Maciej Kuchar, PhD. Eng., Zbigniew Kossowski, PhD. Eng., and Piotr Jozwiak, MSc. Eng., for their help with my research. In addition, I thank Prof. Krzysztof Wituszynski for his help and insightful comments. Also, I cordially thank the reviewers and the Elsevier team, especially Ms. Carrie Bolger, for their cooperation and assistance during preparation of this book.

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CHAPTER

Introduction

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In the current worldwide population of several million vehicles equipped with internal combustion engines, different solutions are employed to obtain increased fuel economy and lower emissions, which are necessary due to increasingly stringent environmental standards [1]. Some are well known, whereas others are still in development. Examples of such solutions include variable valve actuation (VVA), exhaust gas recirculation, direct injection, and hybridization of vehicles. The VVA system adds a few degrees of freedom to control the internal combustion engine.

Tribological processes that occur in the existing valve train with cam-driven valves are well known and described in the literature [2–4]. In current solutions of valve timing with cam drive, the steel valves are used in conjunction with seat inserts and guides of cast alloy. The operation is provided under conditions of mixed friction due to intentional limits on the amount of oil supplied to the contact zones of the valve stem, guide, and valve seats and seat insert. Extortions acting on elements of the guide–valve–seat insert set are repeatable and subject to duty cycle of the engine, applied geometry, and stiffness in the elements of the valve train. Variations in these conditions occur mainly during cold engine warm-up and are short-lived.

Increasing the speed of engines with a cam or camless valve train requires the moving parts, such as valves, to be lightweight to reduce inertia forces loading the timing and the power required to drive it.

A relatively new area of use of VVA engines is hybrid vehicles—electrical, with fuel cells, or pneumatic. In such vehicles, the engine can operate at the optimal operating point due to the load and speed. Due to the necessity for frequent engine shutdown, the VVA engine is best suited to operate in such conditions.

The introduction of new systems of control valves, including the VVA system, changes waveforms of load, relative velocity, and temperature characterizing operation of components of the guide–valve–seat insert system. This results in changes in courses of the resistance of motion in the valve stems against guides and wear intensity for components of those systems. Operational conditions of each controlled system and the type of drive valve are specific to each system because each system has its own unique dynamics based on the algorithm used and the control and drive components. The requirements for increasing the accuracy of control algorithms for valve motion necessitate the consideration of

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changes in the resistance of motion between the valve stem and its guide and the introduction of their compensation.

The use of new lightweight valves, matching seat inserts, and guides made of new materials changes the resistance of motion and wear intensity compared to those of the previously used valves made of steel. The resulting issues that arise have not been sufficiently recognized.

One of the unresolved issues is lubrication. For camless drives, the elimination of some elements of the classic cam-driven timing changes the conditions for the supply of oil to the contact valve stem–guide. This may result in the need to increase oil pressure in the main oil circuit, resulting in more power to drive the oil pump. It may also lead to increased complexity of the oil system and increased resistance to flow because of additional channels supplying oil to bearings of valve drives. As a result, the reduction in power needed to drive the valves will be offset by the increase in power to drive the unit supplying the oil system.

The preferable solution is to eliminate timing from the main lubrication system of the engine. This creates new tribological problems associated with organizing a new way of delivering lubricant to the contact area valve stem–guide or taking actions to prevent the reduction of valve life, despite the elimination of lubrication of moving parts in the timing.

Then, lubrication of the contact valve stem–guide can be provided using, for example, additional oil storage tanks or self-lubricating bushings. Oil selection and design of such bushings require separate tests for each drive configuration. The best solution is to use engine oil and bushings geometry similar to the geometry of classic guides. Complete elimination of oil may be possible in engines of lower speed and power, and it requires careful association of materials for guides and valve stems.

Weights and key dimensions, such as the maximum diameter of the valve head d_g, diameter of valve stem d_t, and total height h_z for valves on the market that are made of steel and TiAl alloys and used in the same engines were measured. The results allow for the assumption of an approximate criterion for classifying valves as lightweight, involving the fulfillment of the following condition [5]:

$$\frac{m_z}{h_z(d_g^2 + d_4^2)} < 0.0004\ g/\text{mm}^3 \tag{1.1}$$

CHAPTER

Principles of valve train operation

2

The operation of valve train elements occurs under conditions of the repetitive operating cycle of the engine and depends on its course and parameters. Therefore, the engine type is one of the principal determinants of valve performance. Most cases of valve trains are seen in four-stroke cycle engines, and only a small portion of cases concern two-stroke engines.

There are two main engine types: spark ignition (SI), operating in a version of the Otto cycle, and compression ignition (CI), which operates in a version of the diesel cycle.

The valve performance is also determined by the type and the method of delivery of the components necessary to carry out the combustion process in the engine, especially fuel and the oxidizer. Both of these and interactions between them have an effect on pressure, temperature, the course of the combustion, and the produced atmosphere in which the valves operate. In SI engines, petrol is the common fuel; however, these engines may be powered with other fuels, such as autogas (LPG), methanol, ethanol, bioethanol, compressed natural gas, hydrogen, and nitromethane [6]. In most cases, CI engines are fuelled with gas oil.

There are also engines that use variable cycles. An example is the Ricardo engine [7], in which the low-speed range of the two-stroke cycle is used and the four-stroke cycle is used at higher speeds. This involves the need to ensure greater efficiency throughout the engine speed range. This engine enables fuel savings of 27%.

Relatively recently, engines with a homogeneous charge compression ignition (HCCI) have been developed that are hybrids of SI engines based on CI engine processes. The HCCI engine combines the high performance of the CI engine with the low NO_x and particulate matter emissions of the SI engine. In the HCCI engine, fuel and air are mixed before combustion, as in the SI engine, and compression of the mixture causes self-ignition in the same way as in the CI engine. There are various methods of HCCI ignition control: inlet air temperature control [8], variable compression ratio [9], dual fuel injection [10], variable valve timing [11], and exhaust gas recirculation [12].

WITHDRAWAL FROM THE BASIC VALVE TIMING

As explained in Ref. [13], the opening and closing of inlet and outlet valves are timed to match the beginning and the end of the induction and exhaust strokes,

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respectively. In the case of a variable-speed motor vehicle engine, such an orderly approach to valve timing would result in highly inefficient operation. In practice, it is necessary to change the basic valve timing implied by the four-stroke or less than two-stroke principle.

The change in timing can be based on the factors involved, such as the following:

1. Inertia effects of the incoming and outgoing cylinder gases
2. The flexible nature of incoming and outgoing cylinder gases
3. Mechanical stresses imposed by rapidly opening and closing valves

To accommodate the previously mentioned effects, the basic valve timing of the four-stroke principle can be modified by providing for the lead (advanced time) and lag (delay time) of the inlet and outlet valve periods of opening.

LEAD, LAG, AND OVERLAP

The concept of lead, lag, and overlap is explained in Ref. [13].

The inlet valve is given a lead in opening before the piston reaches top dead center on the exhaust stroke (Fig. 2.1A) so that least resistance is offered to the incoming flow of air and petrol mixture as the piston begins its induction stroke. It is also provided with a lag in closing after the piston reaches bottom dead center and begins the compression stroke (Fig. 2.1A) so as to take advantage of the reluctance of the incoming mixture to cease flowing as the piston ends its induction stroke. The maximum amount of air and petrol mixture is therefore induced to enter the cylinder, which directly affects the power developed by the engine.

The outlet valve is given a lead in opening before the piston reaches bottom dead center on the power stroke (Fig. 2.1B); thus the burnt gases are already leaving the cylinder under their own pressure as the piston begins its exhaust stroke. As a result, the engine expends less energy on expelling the exhaust gases than would otherwise be the case. The outlet valve is also provided with a lag in closing after the piston reaches top dead center and begins the induction stroke (Fig. 2.1B). This better scavenges the combustion chamber of exhaust gases and lowers cylinder pressure to facilitate flow of the incoming air and petrol mixture.

The opening of the inlet valve before top dead center on the exhaust stroke and the closing of the outlet valve after top dead center on the induction stroke result in a period during which both valves are partially or fully open. This period when the inlet valve opens before the outlet valve closes is termed the *valve overlap* (Fig. 2.1C).

VALVE TIMING DIAGRAMS

The opening and closing points of the valves are often shown in the form of a valve timing diagram (Fig. 2.1C), although these data can be arranged in a table or the