

A New Generation of Optically Accessible Single-Cylinder Engines for High-speed and High-load Combustion Analysis

Takayuki Fuyuto, Takafumi Matsumoto, Yoshiaki Hattori, Ko Kugimoto,
Taketoshi Fujikawa, Kazuhiro Akihama
Toyota Central R&D Labs., Inc.

Hisaki Ito
Toyota Motor Corporation

Copyright © 2011 Society of Automotive Engineers of Japan, Inc. and Copyright © 2011 SAE International

ABSTRACT

Over the last few decades, in-cylinder visualization using optically accessible engines has been an important tool in the detailed analysis of the in-cylinder phenomena of internal combustion engines. However, most current optically accessible engines are recognized as being limited in terms of their speed and load, because of the fragility of certain components such as the elongated pistons and transparent windows.

To overcome these speed and load limits, we developed a new generation of optically accessible engines which extends the operating range up to speeds of 6000 rpm for the SI engine version, and up to in-cylinder pressures of 20 MPa for the CI engine version.

The main reason for the speed limitation is the vibration caused by the inertia force arising from the heavy elongated piston, which increases with the square of the engine speed. To compensate for the inertia force associated with the elongated piston, we used two opposing balancing pistons, in a configuration which is perfectly balanced.

The maximum in-cylinder pressure of current diesel engines exceeds 15 MPa. To enable the study of such high in-cylinder pressures, the elongated piston of the diesel version was designed and optimized using finite element method (FEM) calculation.

This paper describes the details and features of the newly developed optically accessible engines and provides some examples of in-cylinder visualization.

INTRODUCTION

Since the 1960's, in-cylinder visualization using optically accessible research engines has been widely

used for understanding the in-cylinder phenomena of internal combustion engines such as fuel injection, mixing, combustion and emissions formation [1-18]. A precise understanding of these phenomena has been essential to improving the combustion process and reducing engine emissions and fuel consumption. In addition, we rely on in-cylinder visualization to validate computer fluid dynamics (CFD) models, including the spray break-up model and combustion model.

To visualize in-cylinder phenomena, it is common to use an optically accessible single-cylinder engine with an elongated piston. With the basic bottom-view arrangement, the in-cylinder phenomena can be observed through a combination of a window mounted at the top of the elongated piston and a mirror, which is mounted on the cylinder block, angled at 45 degrees to the vertical. This bottom-view configuration using an elongated piston was originally developed by Bowditch in 1961 and used for the visualization of SI combustion [1]. Since then, this configuration has been widely used not only for SI engines, but also for diesel engine analysis [2-17].

To visualize those phenomena that vary in the direction of the cylinder axis, it is necessary to make observations from the side of the cylinder. To this end, a transparent-cylinder engine has been developed [4, 5]. Recently, a fully accessible transparent cylinder, in which the upper surface is shaped in the same way as the pent-roof, has been developed [11, 12].

In the case of a diesel engine with a common-rail injection system, fuel is injected into the squish area as well as into the piston cavity in the early pilot or after injection stages. To observe the spray and combustion behaviors in the squish area, a top-view visualization engine with an optical window in the cylinder head has been developed [6]. Recently, an optically accessible engine that allows

three-directional optical access, with bottom, side and top views, has been developed and used in practical applications [14].

Laser diagnostic techniques are powerful tools for visualizing phenomena that cannot be observed by a direct photography method [12-17]. The 2-D distribution of fuel vapor and NO_x, for example, can be visualized using the planar laser-induced fluorescence (P-LIF) technique. A thin laser sheet is introduced into the combustion chamber to provide excitation, allowing an LIF image to be observed perpendicular to the laser sheet plane. To observe a horizontal distribution, in general, a laser sheet is projected through the transparent window or cylinder that is mounted just below the cylinder head. LIF images can be captured from below the piston, through the transparent piston.

The design of optically accessible engines with elongated pistons can be categorized into two types. One is the single-cylinder type which has been specially designed for research into and analysis of in-cylinder phenomena. The crankcase of this type usually has a balancing mechanism to compensate for the inertia force of the elongated piston. The other is the multi-cylinder type which is a conversion of an actual engine. Usually, one of the pistons of an actual multi-cylinder engine is replaced with an elongated piston and the cylinder block is also elongated [9]. In some cases, all of pistons are replaced with elongated pistons [10]. The crankcase and cylinder head are usually used as is. The latter type is easier and cheaper to prepare than the former, single-cylinder, type. The latter type is inferior, however, for high-speed operation because the crankshaft, originally designed for the engine's actual lightweight pistons, is used as is.

Most existing optically accessible single-cylinder engines are, however, recognized as being limited in terms of speed and load, because of the fragility of certain components such as the elongated pistons and transparent windows. Many are limited to speeds of less than 3000 rpm. There have, nevertheless, been a few optical single-cylinder engines that can run at high speeds and/or under high loads. The gasoline engine developed by Pitcher et al. can run at 5000 rpm [11, 12]. In addition to a bottom-view, it also allows us to observe the entire pent-roof area from the side. They used this engine to observe the in-cylinder fuel spray of a direct injection system. The diesel type developed by Hotta et al. allows us to visualize combustion at high speeds of 4000 rpm and under high loads (maximum in-cylinder pressure = 12 MPa) [8]. The bottom-view window of this engine is made of sapphire, instead of the conventional quartz, to increase the strength of the elongated piston while reducing its weight. Currently, an optically accessible single-cylinder engine is typically limited to 5,000 rpm and 12 MPa, which doesn't cover the operating range of actual gasoline and diesel engines.

Current trends in the development of both gasoline and diesel engines include high-pressure charging and downsizing, which tend to increase the load

imposed on the engine. In addition, improving combustion at the maximum power output is still very important for both driving pleasure and customer appeal. It is necessary, therefore, for in-cylinder imaging analysis to be possible over the entire operating range, including high speeds and high loads, when developing new engine combustion systems.

To overcome the speed and load limits, a new generation of optically accessible engines was developed which extends the operating range to 6000 rpm for the spark-ignition (SI) engine version, and to in-cylinder pressures of 20 MPa for the compression-ignition (CI) engine version.

INCREASING THE MAXIMUM OPERATING SPEED

PROBLEMS THAT OCCUR AT HIGH SPEED

The main reason for imposing a speed limit on an engine is the inertia force created by the heavy elongated piston, with the wide bottom-view window. This inertia force increases with the square of the engine speed. The inertia force induces vibrations both in the engine itself as well as in the optics such as cameras, mirrors etc., such that the visualization becomes very difficult. In addition, this strong inertia force presents a safety problem in that there is a danger of the moving parts failing.

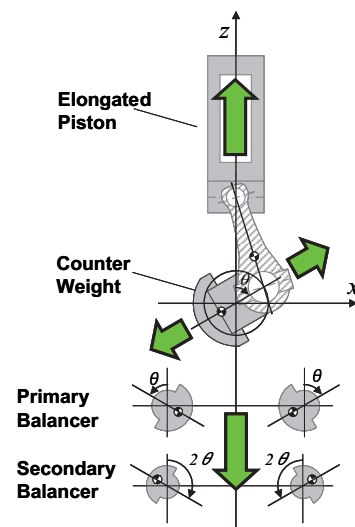


Fig. 1 Basic balancing mechanism of optically accessible engines with elongated piston

First, we introduce a balancing mechanism that is commonly used in existing optically accessible engines (Fig. 1). Many optical engines have balancer shafts that rotate symmetrically in order to compensate for vertical inertia force of the elongated piston and the smaller end of the connecting rod. The horizontal inertia force induced by the centrifugal force on the larger end of the connecting rod and the crank

shaft is canceled by the counterweight attached to the crankshaft, while the overbalance rate is designed to be 0%. Some optical engines only have 1st-order balancers. Others, which are designed to operate at high speed, have 2nd-order balancers rotating at twice the speed of the crankshaft in order to cancel out the 2nd-order inertia force on the elongated piston.

Increasing the speed to over 6000 rpm leads to the appearance of three new problems. The first problem is mechanical damage to the crankshaft, the second problem is friction damage to the shaft bearings, and the third is tensile failure of the connecting rod bolts.

The third problem was solved by enlarging the diameter of the bolts and changing their material. The bolt diameter was made as large as possible within the spatial limit, specifically, 16 mm. The material was changed to a special steel alloy with a tensile strength 1.6 times greater than that of conventional chrome molybdenum steel. The other two problems remain difficult to solve.

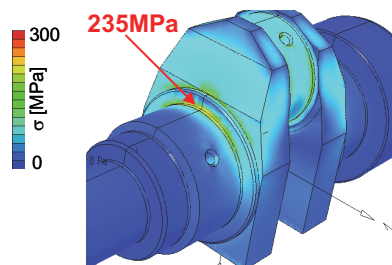


Fig. 2 Result of FEM analysis on a crank shaft assuming that it rotates at high speed of 8000rpm, thus introducing a considerable margin.

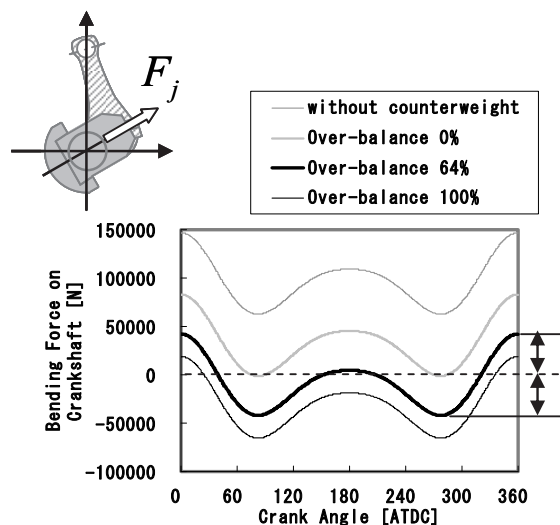


Fig. 3 Relationship between bending force on crankshaft, F_j , and overbalance rate

Figure 2 shows the results of FEM analysis on a crankshaft, assuming that it rotates at a high speed of 8000 rpm, thus introducing a considerable margin. The inertia force and centrifugal force acting on the elongated piston and connecting rod combine to apply a bending force to the crankshaft. The maximum value of the local stress induced by the bending force exceeds the acceptable range for the material, such that mechanical damage would be caused to the crankshaft.

Figure 3 shows the relationship between the bending force on the crankshaft, F_j , and the overbalance rate. The direction of the bending force is defined from the crankshaft to the crank pin, as shown in Fig. 3. If the overbalance rate is 0%, F_j is positive almost all the time while the crankshaft rotates through 360 degrees. Therefore, the crankshaft is consistently pushed in the direction of F_j , thus inducing friction damage to the shaft bearings.

To solve these two problems, it is necessary to increase the mass of the counterweight and so establish an "overbalance." The authors increased the mass-moment of the counterweight to minimize the bending force F_j and the bearing surface pressure, by equalizing the maximum value of F_j at TDC and the absolute of the minimum value of F_j to around 90 deg. ATDC and 270 deg. ATDC (Fig. 3). In the example case shown in Fig. 3, the optimum overbalance rate was approximately 64%. FEM analysis under this optimum condition showed that the stress distribution remained within the acceptable range.

This increase in the counterweight mass-moment, however, induces an imbalance, which is caused by the increment in the centrifugal force $\Delta F1$ (Fig. 4, left). To eliminate this imbalance, left-right asymmetry 1st order balancers (Fig. 4, right), can be implemented instead of the symmetry balancers. In this configuration, the increment in the centrifugal force of

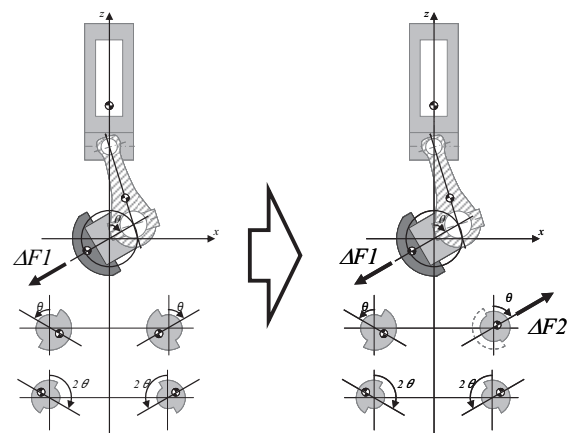


Fig. 4 Imbalance caused by the increase of counterweight mass-moment (left) and its countermeasure, left-right asymmetry 1st order balancers (right)