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Variable valve timing for fuel economy improvement in a small spark-ignition engine

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ABSTRACT

The potential of a simple variable valve timing (VVT) system has been investigated. This system has been designed to update a small displacement engine pursuing the objective of optimizing both engine performance and, particularly, fuel consumption at part load operation. A continuously variable cam phaser (CVCP), able to produce a reverse Miller cycle effect during the intake phase and a significant internal EGR generation at the end of the exhaust stroke, has been introduced. A numerical approach, based on both 1-D and 3-D computational models, has been adopted in order to evaluate the engine performance when load is controlled by the VVT system and to deeply investigate the influence, on in-cylinder phenomena, of the valve timing variation. In this way, the VVT system here analyzed revealed as an effective tool in reducing the pumping losses, hence the specific fuel consumption, at partial load.

1. Introduction

The European Union has recently signed the Kyoto protocol. Thus, the control of green-house gas emissions has begun to add to the numerous constraints that vehicle manufacturers have to satisfy. The reduction of engine fuel consumption becomes a primary requirement as well as meeting current and future emission legislations.

Naturally, talking about reduction of engine fuel consumption means to keep unvaried, sometimes improved, the performance level of current engine production. Dealing with engine topics exclusively, improving fuel economy to reduce CO_2 emissions means improving the engine thermal efficiency.

As it is usual in engine management, this target can be met following different routes, each of them could be an effective way with different cost-to-benefit ratio. Often, it could be observed, it is helpful to adopt numerous solutions contemporaneously. As an example, fast combustion, lean burn, variable valve timing and actuation, gasoline direct injection and so long may be reminded.

During most of its average life, a road engine is run under low load and low speed conditions. It is known that load reduction in spark-ignition engines is traditionally realized by introducing additional losses during the intake stroke by means of a throttle valve. In these operating points, the engine efficiency decreases from the peak values (already not very high) to values dramatically lower.

The optimization of intake and exhaust valve timing can provide significant reductions in pumping losses at part load operation [1–3]. In this paper, the benefit of engine load control performed by using a simple variable cam phaser has been analyzed and the influence of the VVT strategy on the combustion process and engine performance has been evaluated.

1.1. The engine

The engine under study (Table 1) derives from a small displacement (1.4 l), 2 valves per cylinder, MPI engine developed in late 1980s.

The objective of this paper is to contribute to the development of an up-to-date version pursuing, among others, the target of improving engine fuel economy. To this aim, the adoption of a continuous variable valve timing (VVT) system, able to optimize engine torque and efficiency, has been considered [4].

In particular, the VVT technology here proposed is mainly aimed to the load control and the generation of internal exhaust gas recycle (EGR) rather than to the volumetric efficiency optimization. Due to economic constraints, the engine architecture with a single camshaft for the valve actuation has been kept.

A continuously variable cam phaser (CVCP), able to shift the overhead camshaft to retarded positions at constant overlap [5] (Fig. 1), has been chosen. This simple and economic system allows a load control shared between CVCP and throttle. Delaying all valve

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Table 1
Main baseline engine characteristics

Total piston displacement (cm^3)	1368
Bore (mm)	72.0
Stroke (mm)	84.0
Cylinder number	4
Valve number	8
Geometrical compression ratio (–)	11.0
Valve timing (Intake–exhaust) (°)	7/41–55/–7

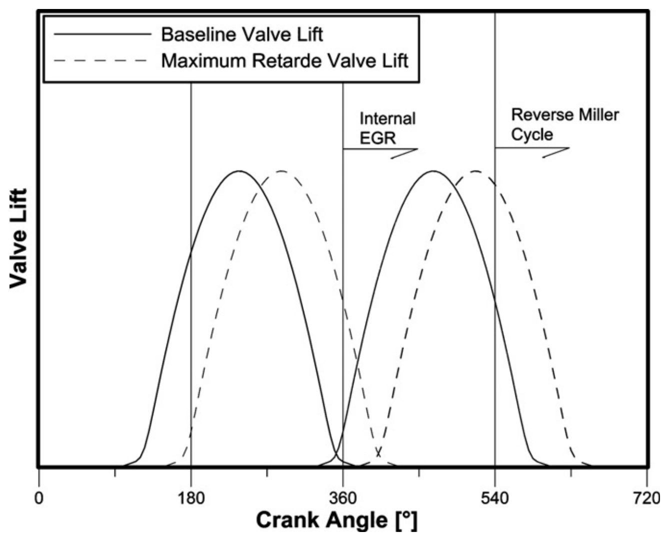

Fig. 1. Due to exhaust gas re-aspiration and intake backflow, retarded valve events penalize the engine volumetric efficiency. At wide open throttle, delaying the valve timing the engine load decreases while the internal EGR ratio increases. (Dashed line: exhaust valve lifts; solid line: intake valve lifts).

events, an intensive backflow at the intake end occurs (reverse miller cycle) and a large amount of exhaust gas comes back into the cylinder (internal EGR).

Combining reverse miller cycle and internal EGR a significantly high de-throttling effect can be achieved, thus reducing the pumping losses at part load and improving the fuel economy in many driving conditions.

Obviously, the engine load control by means of the CVCP system at fully un-throttled operation is limited by the EGR tolerance of the engine. In order to improve this engine characteristic at medium and low loads, when the engine is operated at high EGR rate, a particular exhaust port geometry, able to generate a variable swirl motion of recirculated exhaust gases, has been designed. In detail, an exhaust valve masking has been adopted in order to generate an intensive swirl motion of the re-aspirated exhaust at low valve lifts. Combining this effect with the swirl motion generated during the late intake process allows obtaining a high turbulence level at part load, improving the combustion quality and making tolerable high charge dilutions. (in Fig. 2, some details of the prototype engine are illustrated). Thus, optimized port-valve designs could provide high turbulence levels and high volumetric efficiency in order to achieve both satisfying fuel economy at part load and appreciable full load performance.

2. Numerical approach

CFD modeling has been utilized in order to both understand the engine in-cylinder phenomena and provide guide lines for the experimental tests aimed to find the optimal solutions.

Preliminary analyzes have been carried out to estimate the behaviour of the baseline engine using the CVCP system. A numerical analysis has been performed by means of a 1-D code able to simulate the whole thermodynamic cycle.

These preliminary results showed the effectiveness of this approach. The high calculated EGR rates showed the need of improving the in-cylinder turbulence level in order to obtain optimal combustion rates and stability at medium and low loads. The generation of a swirl motion, produced by the recirculated exhaust gases, has been considered to reach this target.

Furthermore, 3-D analyzes have been carried out in order to obtain both a correct design of the exhaust port (steady-flow analysis) and a sound explanation of the phenomena occurring when the engine valve timing yields deep modifications of the in-cylinder flow field and combustion process (transient analysis).

The 3-D simulations have been performed by the 7.3b standard release of the AVL FIRE code [6,7]. The processor allows solving the ensemble-averaged governing equations of the flow and the heat transfer within the computational domain either for steady-state or for transient analysis in moving grids. For engine applications, the code dynamically modifies the grid according to the valve lift diagram and the piston kinematics; the rezone subroutine allows re-mapping the calculated field between grids with different resolutions. The problem of the unknown turbulence correlation is resolved through a compressible version of the standard two equations k–ε model. The partial differential transport equations are discretized on the basis of a finite volume method. The temporal discretization is Euler implicit. Hybrid and CTVD differencing schemes are used for the approximation of the spatial derivatives. The coupled set of algebraic equations is solved iteratively based on a pressure–velocity coupling procedure. Each algebraic equation system is worked out by the GCCG solver (Orthomin solver) [8].

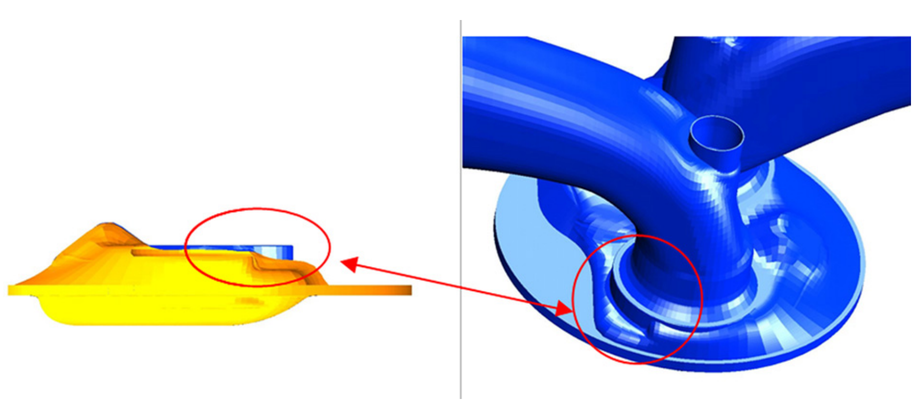

Fig. 2. Combustion chamber cross section (left), ducts and combustion chamber drawing (right). The valve masking is highlighted.