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EGR control of pressure-wave supercharged IC engines

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Abstract

This paper addresses the problem of exhaust gas recirculation occurring when pressure-wave superchargers are used as boosting devices for IC engines.

During hard accelerations, critical situations arise whenever large amounts of exhaust gas are recirculated over the charger from the exhaust to the intake manifolds of the engine. Such recirculations cause the engine torque to drop sharply and thus severely affect the driveability of the vehicle. In order to prevent such situations, the actuators such as throttles, valves, etc., have to be controlled in a coordinated way. Such a control system and its model-based design and verification on an engine test bench are described here in detail.

Keywords: Exhaust gas recirculation; Pressure-wave supercharger; Downsizing; Supercharging; Driveability

1. Introduction

Engine downsizing and supercharging became one of the most widely discussed approaches in Europe as soon as the European automobile manufacturers association (ACEA) made the commitment to reduce average carbon dioxide emissions to 140 g/km for new passenger cars sold in Europe starting in 2008. Passenger cars in urban areas are mostly operated under part-load conditions. In these operating conditions gasoline engines inherently suffer from a lower efficiency than compression-ignited engines since the load is controlled by throttling the engine's mass flow, i.e., by reducing the pressure in the intake manifold. This method is simple and entails excellent dynamic behavior, but it induces pumping losses. Particularly for low loads the efficiency of the engine becomes very poor. As the displaced volume directly correlates with the friction losses, it has to be reduced for better efficiency.

An engine concept resulting in the same nominal power as the standard engine described above requires either the pressure in the intake manifold or the rotational speed of the engine to be increased. Since high rotational speeds are not accepted well by consumers, the only practicable way is to increase the pressure before the engine. This approach is known as the *downsizing and supercharging concept*.

In the 1970s and 1980s research about supercharged SI engines mainly focused on power performance. In the 1990s, however, supercharged SI engine applications reappeared as a feasible solution for reducing fuel consumption. The potential downsizing and supercharging concept has then been demonstrated experimentally in the *SmILE* engine concept (Guzzella & Martin, 1998; Guzzella, Wenger, & Martin, 2000) as well as later in several series production cars. In such an engine system, the maximum engine torque reduced by a smaller displaced volume is recovered by a higher density of the air mass flow through the engine. The efficiency of the downsized engine for a set of typical operating points, such as the European driving cycle (MVEG-95), is higher than that of the naturally aspirated engine with a similar maximum torque. Thus, the cumulative fuel consumption at the end of the cycle is lower.

Three main types of superchargers are in use today with the purpose of achieving a higher intake manifold pressure: mechanical superchargers (MSC), turbochargers (TC), and pressure-wave superchargers (PWS). Whereas MSC such as

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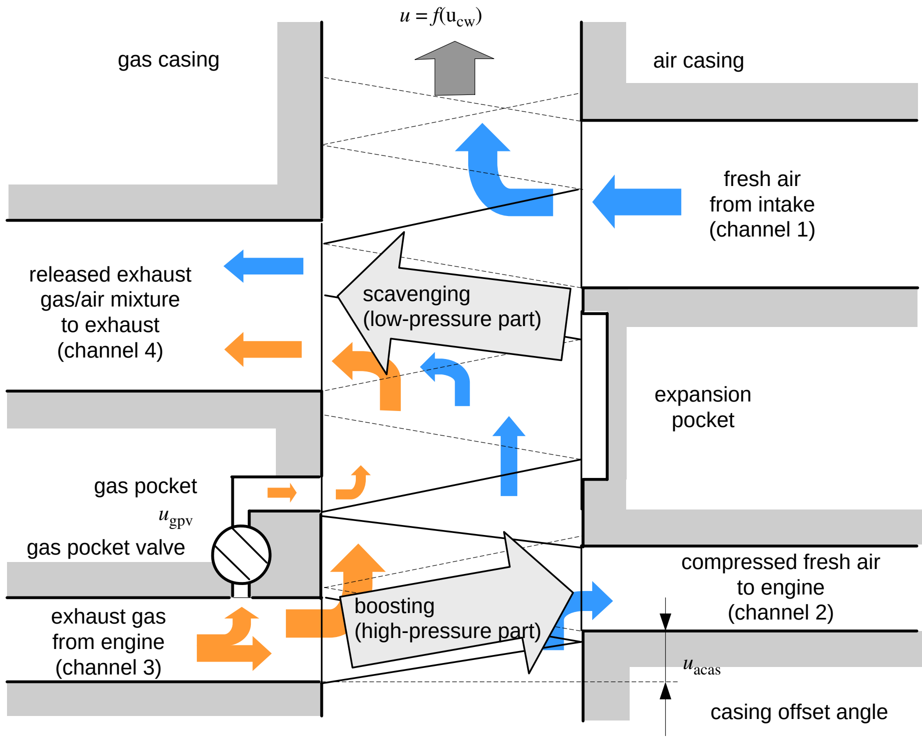

Fig. 1. Schematic overview of the pressure-wave supercharger: four channels (channel 1–channel 4) and two pockets (gas pocket channel, expansion pocket) are linked to the rotating cell wheel. Three actuators affect the pressure-wave processes: The gas pocket valve (u_{gpv}) brings the amount of energy required for boosting to that necessary for scavenging. The cell-wheel speed (u_{cw}) and the offset angle of the casing (u_{acas}) guarantee the best charging efficiency. This optimum is reached for well-tuned operating conditions, i.e., when the opening and closing events of the channels correspond to the running times of the pressure waves.

blowers, compressors, or pumps are driven by the crank shaft or by an electric motor, for TC and PWS some of the exhaust gas enthalpy is transmitted to the air mass flow entering the engine to raise the intake manifold pressure above the ambient level. For turbocharging, a turbine in the exhaust path is used to drive a radial compressor, which pumps air into the intake manifold. In contrast, the core of the PWS is the so-called cell wheel, a set of open-ended channels arranged on a rotor between two casings. During a cycle, a cell is passing the exhaust manifold, where the entering gas triggers a shock wave that runs through the cell and compresses the fresh air. This compressed air then leaves the cell in the direction of the intake manifold (Gyarmathy, 1983).

Exhaust gas recirculation (EGR) is a phenomenon often encountered in PWS since in a PWS fresh air and exhaust gas are in direct contact in the cell wheel. Depending on the concept, EGR has to be reduced (in spark-ignited engines) or forced (in compression-ignited engines). Flow resistances in the exhaust system, i.e., where the exhaust gas is released to the ambient, have to be minimized since the pressure-wave process only works with very low back pressures. Moreover, the problem is exaggerated during the engine warm-up since much of the energy in the exhaust gas is transferred to the walls.

Although the PWS concept of boosting diesel engines lost out to turbocharged engines in the 1990s, the PWS with its potential and advantages keeps being proposed as a viable alternative. State-of-the-art PWS are quite different from those of earlier times. Modern devices such as the HYPREX® PWS[1] have been basically redesigned, and research in materials has made considerable progress as well. More freedom in the positioning of the device and maximum efficiency can be obtained over the entire operating range if the cell wheel is driven separately using an electric motor. The cold-start behavior is improved by the reduction of the angular offset between gas and air casing. Last but not least, substantial progress has been made in the last 20 years in providing powerful computers such that even complex on-board computations are now feasible in real time. They permit effects such as those appearing in a PWS to be predicted with sufficient accuracy such that they can be controlled.

2. The PWS

In pressure-wave machines such as the PWS, pressure-wave exchanger (PWE) or wave-rotor (WR) energy is transferred between two gaseous fluid streams by short-time direct contact of the fluids in narrow flow channels, the so-called cells (see Fig. 1). Pressure-wave machines make use of the physical fact that if two fluids of different pressures are brought into direct contact, pressure equalization

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