

Pneumatic Regenerative Engine Braking Technology for Buses and Commercial Vehicles

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ABSTRACT

In this paper, a novel cost-effective air hybrid powertrain concept for buses and commercial vehicles, Brunel Regenerative Engine Braking Device (RegenEBD) technology, is presented and its performance during the braking process is analysed using the Ricardo WAVE engine simulation programme. RegenEBD is designed to convert kinetic energy into pneumatic energy in the compressed air saved in an air tank. Its operation is achieved by using a production engine braking device and a proprietary intake system design. During the braking operation, the engine switches from the firing mode to the compressor mode by keeping the intake valves from fully closed throughout the four-strokes by installing the Variable Valve Exhaust Brake (VVEB) device on the intake valves. As a result, the induced air could be compressed through the opening gap of intake valves into the air tank through the modified intake system. The compressed air can then be used to drive an air starter to achieve regenerative stop-start operations. The RegenEBD technology has been implemented and demonstrated on a production vehicle with the existing vehicle transmission system by retrofitting the VVEB and adding a sandwich block between the cylinder head and the production intake manifold.

A Yuchai 6A six-cylinder 7.25 litre diesel engine used on city buses in China has been modelled as an air hybrid engine and analysed using Ricardo's WAVE engine simulation software. The results show that for a 151 litre air tank, it takes 120 engine revolutions for charging the air tank pressure from 4 bar to 6 bar (4.8 seconds at 1500 rpm engine speed). During stop-start operations, the engine could theoretically be cranked directly by the compressed air through fast acting valves but in this study, it is cranked by means of a standard production air starter motor.

In addition, a new air hybrid vehicle driving cycle simulation programme has been developed and applied to analyse the charging and discharging processes during a typical London Bus route. The analysis shows that with the RegenEBD almost all the idling periods can be eliminated through regenerative stop-start operations, resulting a fuel saving of 6.2%. For commercial vehicles, the regenerative compressed air supply can also be used to provide service air in place of the engine driven compressor for additional fuel savings. Furthermore, the compressed air can provide the instant boost for better vehicle performance and further fuel savings.

INTRODUCTION

As the major fuel savings come from regenerative stopstart operations, it would be most beneficial for the hybrid powertrain to be used in city buses which have the most frequent stop-start operations and long idle periods. This has resulted in the development and deployment of a number of electric hybrid buses in New York and London over the last few years. The buses with hybrid powertrain in London achieved on average around 15% fuel saving compare to diesel buses [1]. However, it is noted that in some cases the installation of the electric hybrid powertrain caused increased fuel consumption because of inadequate calibration and optimisation. However, the fuel saving is obtained at a hefty price for such hybrid powertrain technologies. It is reported that a hybrid double-decker bus costs GBP 300,000 as against GBP 200,000 for one with a conventional diesel engine [2]. For a hybrid bus with 30% reduction in fuel consumption, the annual saving is around GBP4,500-GBP5,000 a year in London [2] and the payback period is therefore estimated to be about 20 years.

Compared to Hybrid Electric Vehicles (HEVs), Hydraulic Hybrid Vehicles (HHVs) have high braking power density and can be well suited for vehicles with frequent stopstart

operations. Series HHV components has been developed by Eaton Corporation et al and utilized in parcel delivery vehicles owned by United Parcel Service (UPS) [3]. In this series HHV, the engine, linked to the drive wheels only by the hybrid hydraulic drive system components, indicates that the base vehicle transmission has been replaced. This serious HHV demonstrated up to 50% fuel saving and 30% reduction in carbon emissions in real world use. The regenerative efficiency could be as high as 71% [4]. In addition, the Dutch company Innas has also developed its series HHV and predicted results show that more than 50% of fuel saving for a 1450 kg passenger car could be achieved throughout the NEDC [5-6]. Furthermore, Parker has also developed a serious hydraulic hybrid vehicle system for refuse truck. The system is able to capture and reuse more than 70% of braking energy [7].

Both HEVs and HHVs involve significant and costly modifications to the vehicle's powertrain and transmission system, as well as the additional weight and space for batteries and motors. In this paper, we will present a novel cost effective air hybrid technology, regenerative engine braking device (RegenEBD). The RegenEBD technology utilizes the existing engine braking device and production components. It is capable of regenerative stop-start operations and technology and has no any modification on the transmission system to achieve stop and start operations especially benefits Buses and delivery vehicles.

CONFIGURATION OF THE AIR HYBRID ENGINE

Figure 1 shows one of the 6-cylinders of a Yuchai YC6A 7.25 litre diesel engine widely used in the inner city buses in China modified for air hybrid operation. Air flows through the intake valves (5 and 6) via a siamesed intake port (7) and leaves exhaust valves (3) via exhaust port (4). Intake valve 5 and Intake valve 6 can be actuated jointly by a VVEB device. The VVEB device is designed for engine braking applications, Fig.2, and is normally installed on the exhaust valves. When it is actuated, the small piston is forced down by the hydraulic pressure and the valve will be stopped with a 1-2mm adjustable lift. A non-return Reed valve (8) is additionally provided in the intake port (7). While air pressure downstream of the Reed valve is lower than the pressure in the intake manifold, the Reed valve pedals open and air is induced into Intake port 7. On the other hand, if air pressure inside the auxiliary chamber formed between the intake valves and the Reed valve is higher than the pressure in the intake manifold, the Reed valve pedals close and air will be kept within the intake port.

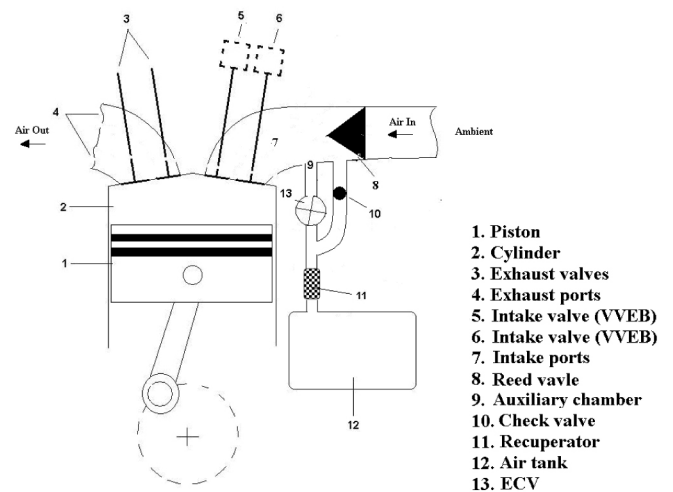


Figure 1. Schematic diagram of an air hybrid engine with an Energy Control Valve (ECV).

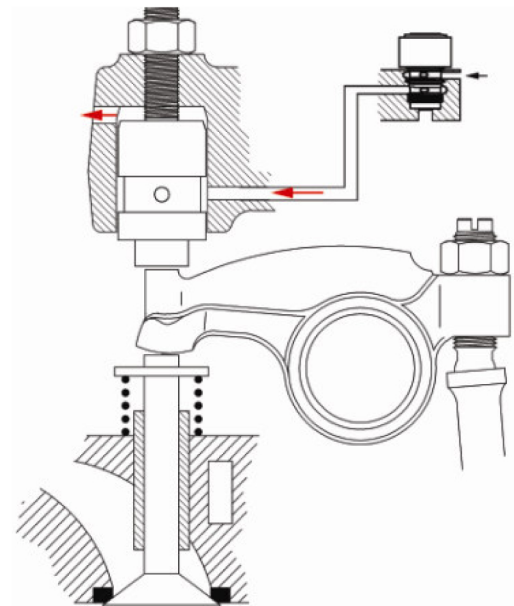


Figure 2. Schematic of the VVEB device [8]

The Energy Control Valve ECV (13) is a solenoid valve that controls air flow out of the air tank (12) for the cranking mode operation. In addition, a check valve (10) has been adopted to control the air flow into the air tank (12) during the compressor mode (CM) operation. The air tank is connected to intake port 7 through a recuperator (11). Such a recuperator can be used to absorb and store heat energy when compressed air is accumulated from cylinders to the air tank in the CM. It would return heat energy back to the compressed air from air tank to cylinder in the cranking mode. Therefore, high temperature and high pressured compressed air could be reused. Recuperator 11 is not modelled separately in the analysis but the compressed air

will be assumed to retain their temperature in the air tank which is equivalent to 100% recuperator efficiency.

THE PRINCIPLE OF OPERATION

Figure 3 and 4 show the valve timing diagrams and the gas exchange processes respectively for the normal firing mode, CM and the cranking mode. During the normal firing mode, both intake and exhaust valves operate with their default lift profiles. During deceleration and braking, fuel injection is switched off, both intake valves are opened by the stock cam through the pushrod and rock arm during the intake stroke and then remain slightly open (1.25 mm lift) by the action of the VVEB device throughout the rest of the four-stroke cycle so that the air is compressed and stored in the auxiliary chamber formed by the one-way Reed Valve, the Check Valve and the ECV. As a result, the engine will be operated as a compressor driven by the kinetic energy of the moving vehicle. When the cranking operation is desired, the ECV opens during the normal expansion stroke so that the compressed air can flow through the opening intake valves due to the action of the VVEB device and forces the piston down and generates the motoring work. However, as it will be shown later that the net cranking torque is reduced by the compression work done on the air inducted during the intake stroke.

The size of the auxiliary chamber volume is determined by the position of the non-return Reed valve, the position of the check valve and the position of the ECV. The geometric compression ratio of the engine is 17.5:1 for the normal firing mode. However, when the engine is switched to the compression mode, the actual compression ratio (R_c) decreases as the volume of the auxiliary chamber is included in the cylinders' total clearance volume. The Reed valves are mounted inside a sandwich block which is installed between the cylinder head and the original intake manifold. The check valves at the bottom of the sandwich block are connected to the hoses to the air tank. Based on the position and geometry of the Reed valves, the auxiliary chamber volume is found to be 260cm³. Hence the actual compression ratio is calculated as:

$$R_c = \frac{1143 + 69 + 260}{69 + 260} = 4.5 : 1 \quad (1)$$

During the CM operation, air is compressed into the auxiliary chamber before it flows through the check valve into the air storage tank due to the pressure difference between the auxiliary chamber and the air storage tank. During the cranking mode, the ECV controls the amount of compressed air released from the air storage tank to the auxiliary chamber and then flows into the cylinder after the intake valve is opened.

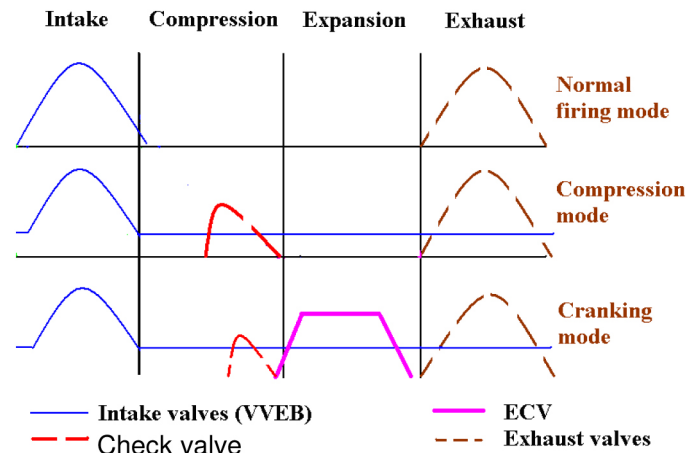


Figure 3. Engine valves, check valve and ECV timing for normal firing mode, CM and cranking mode

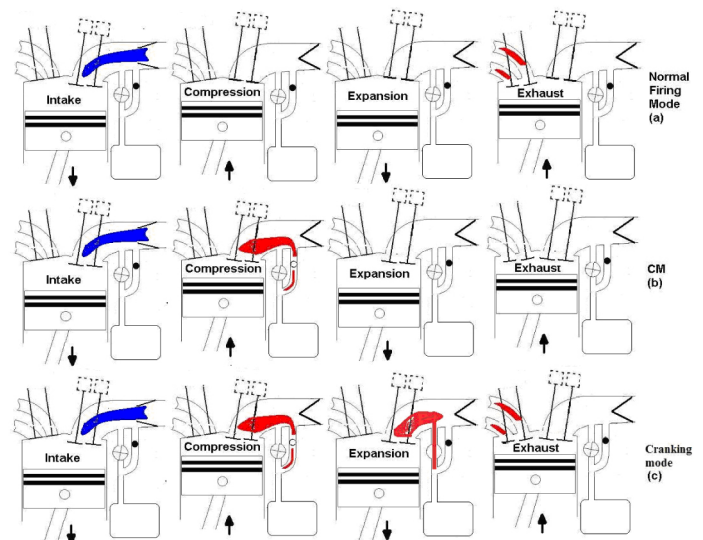


Figure 4. Four-stroke engine cycle for the normal firing mode (a), CM (b) and the cranking mode (c).

SIMULATION AND RESULTS

ENGINE SIMULATION SETUP

Details of the engine and characteristics of various valves are given in Table 1 and Table 2 respectively. A standard 151 Litre air tank as used on a bus has been used in the model. The air tank is designed to have a maximum operation pressure of 10 bar. The engine simulation programme, WAVE, is used to study the gas dynamics of the 6-cylinder engine and its air hybrid operations.

Table 1. Engine dimensions and characteristics

Number of cylinders	6
Cylinder bore	105mm
Piston stroke	132mm
Connecting rod length	210mm
Displacement volume	1143cm ³
Clearance volume	69cm ³
Total volume of one cylinder	1212cm ³
Compression ratio	17.5:1
R _c for air hybrid mode	4.5:1

Table 2. Valves dimensions and characteristics for each cylinder

Intake valve	2
Diameter	32.5 mm
Opening point (normal)	61° BTDC
Closing point (normal)	91° ABDC
Maximum lift	9.6 mm
Exhaust valve	2
Diameter	29.5 mm
Opening point	105° BBDC
Closing point	67° ATDC
Maximum lift	9.7 mm
Reed valve	1
Pedal stiffness	1900 N/m
Maximum lift	9 mm
ECV count	1
Diameter	25.4 mm

VALVES LIFT PROFILE FOR CM

Figure 5 shows the intake valve lift diagram, check valve opening period, and the standard exhaust valve lift diagram. During the CM operation, the VVEB device is actuated on both intake valves so that they will remain open at 1.25mm above the valve seats after the intake process.

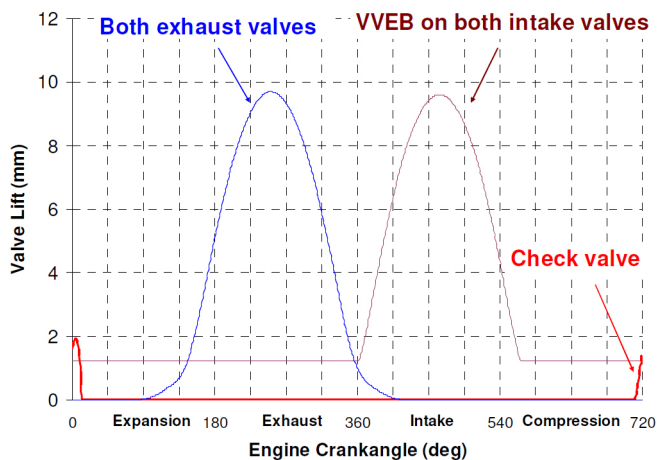


Figure 5. Valve timing diagram for compression mode

Figure 6 shows that the auxiliary chamber pressure trace overlaps with the in-cylinder pressure profile because of the opening intake valves by the action of VVEB. Comparing Figure 5 and Figure 6, it can be seen that the check valve opens close to TDC in the compression stroke when the auxiliary chamber pressure becomes higher than the tank pressure.

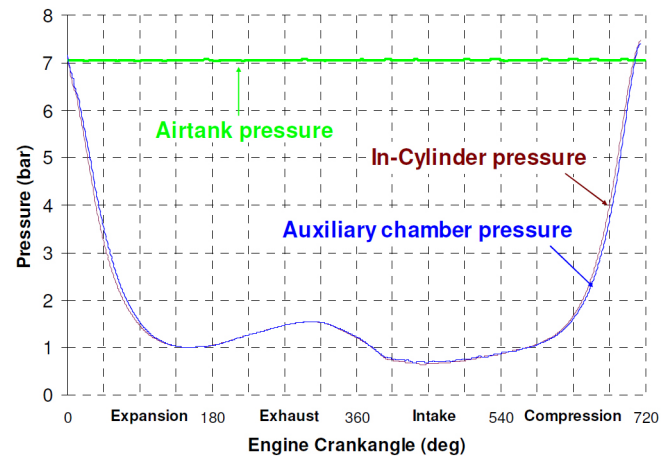


Figure 6. Pressure diagram for compression mode

Figure 7 shows the value of air tank pressure after 120th, 240th and 360th engine revolutions at 1500rpm engine speed during the CM operation when the air tank is charged from ambient pressure. The results show that the air tank can be charged from 1bar to 7.1bar within 9.6 seconds at 1500rpm engine speed. However, it is more important to note that it takes 4.8 seconds to charge the air tank from 4.3 bar to 6.1 bar. As to be discussed later, when a typical air starter is used for stop-start operations, the supply pressure should be above 4.5 bar and the pressure would drop by roughly 0.5 bar after each start. Thus, after less than 5 seconds braking, the air tank would have been charged sufficiently to start the engine.

Figure 8 shows the corresponding engine braking torque values for the 6 individual cylinders at 120th, 240th and 360th engine revolutions at 1500rpm engine speed. The cylinder number is included in the diagram to show the firing order of 6 cylinders. At 120th engine revolution, according to Fig.7 and Figure 8, the tank pressure has reached to 4.3 bar and the peak engine braking torque reaches 250 Nm. The tank pressure reaches 7.1 bar after 360 engine revolutions, the peak engine braking torque approaches 210 Nm. Before the air tank is fully charged, the compressed air is captured by the check valve when the auxiliary chamber pressure is higher than the air tank pressure. As the air tank pressure increases, the check valve opening period decreases. As a result, greater expansion takes place after TDC, resulting in lower engine braking torque seen.