

A Pneumatic Hybrid System with an Integrated Compressor/Expander Unit for Commercial Vehicles

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ABSTRACT

Braking energy recovery can significantly contribute to fuel economy and emission reduction, particularly for commercial vehicles driving in urban environment. By using the compressed air storage, rather than expensive and vulnerable batteries, this paper proposes a pneumatic hybrid system with an integrated compressor/expander unit (CEU) for commercial vehicles, in order to achieve stop/start function and braking energy recovery. During braking, the compressed air is recovered by CEU working in compressor mode and is charged to the air tanks. When the vehicle starts from stop, the CEU works as an expander to crank the engine with compressed air. The compressed air can also be used to supply the air tank of brake boost system, thus reducing its energy consumption. The mathematical models of energy conversion units, including the two modes of CEU and the air brake system, are established and analyzed. A preliminary case study of an urban bus application shows that, in an urban driving cycle, the compressed air recovered from braking is sufficient both for engine cranking and air brake system. Together with the achieved stop/start function of the pneumatic hybrid concept, the total fuel consumption can be reduced by 5.3%, compared to the conventional vehicle case.

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INTRODUCTION

Advanced technologies to improve the fuel economy and to reduce emissions are always in urgent demand in automobile industries. Among these technologies, braking energy recovery is one hot topic and it can effectively contribute to fuel economy improvement and emission reduction.

Braking energy occupies a significant amount of traction energy, especially in urban driving. According to reference [1], braking energy in typical urban driving cycles may reach up to more than 34% of the total traction energy. Researchers from both academia and industries have been studying on diversified approaches of braking energy recovery, including battery-based, high speed flywheel, hydraulic-based innovations, etc.

Hybrid electric vehicle (HEV) shows a successful application of braking energy recovery. With different sizing configuration of electric machine and ICE, different levels of hybridization can be achieved, ranging from micro or mild hybrid, strong or full hybrid, to plug-in hybrid. In micro/mild hybrids, an integrated starter/generator (ISG) system is adopted to realize stop/start function. For full or plug-in hybrids, downsized engines may be adopted, while much stronger electric machines and batteries are necessary. Electric machines can be used in generator mode during vehicle braking, converting the kinetic energy to electro-chemical energy to be stored in batteries. Different from

batteries, hydraulic accumulator is used on hybrid hydraulic vehicle, in which braking energy could be recovered by hydraulic pump/motor unit [2]. For both HEVs and hydraulic hybrids, the additional complexities, cost and weight may be the main challenges in application, particularly for commercial vehicles where the conventional engines are extensively adopted and the corresponding customers are price-sensitive to most advanced technologies.

As another alternative approach to braking energy recovery, hybrid pneumatic engine (HPE) has attracted much attention in recent years [3]. With limited modifications, the ICE could work as a compressor, recovering the braking energy as compressed air. Then the compressed air can be used to start the engine/vehicle, to supercharge the ICE or supply the air demand from the other pneumatic accessories. The main parts added on the hybrid pneumatic vehicle include the air tank and charge valves, which may hopefully be more cost-effective than battery.

Schechter investigated the different modes of hybrid pneumatic engine, where the compressed air comes from the compressor mode and is used at air motor mode or the air power assisted combustion mode [4]. The round-trip energy conversion and recovery is estimated up to more than 60%. Compared to the same rated power naturally aspirated engine, Püritsch et al. showed that the pneumatic hybridization, while combining with

downsizing and supercharging, can not only save fuel consumption but also eliminate the turbo-lag [5]. The viability of the hybrid pneumatic engine is shown by experiments either at all modes alone or at transient modes switches. Lee et al. proposed a mild air hybrid engine, concluding that main contribution to the fuel consumption improvement is the fuel saving by canceling ICE idling [6]. In order to achieve better recovery of braking energy and increase the regenerative braking torque, some researchers proposed the double tank compressor mode [7][8]. In most literature on HPE, both the compressed air regeneration (by compression braking in cylinder) and utilization (in air motor mode or supercharging mode) are achieved within the ICE cylinder. With this in-cylinder HPE approach, the compressed air utilization may be realized more flexibly and optimally for fuel economy improvement, but the cylinder head must be modified and all the air charging valves must be designed and precisely controlled.

As a simplified and less expensive approach, braking energy recovery of HPE can be realized in out-of-cylinder ways, e.g. using a specified compressor coupled in the driveline but out of the ICE cylinder. Ma & Ma designed a hybrid pneumatic concept with ICE supercharger to recover the braking energy as compressed air, which is used for supercharged combustion during rapid acceleration of vehicle [9]. Gilberti proposed a pneumatic start-stop system with the air regeneration compressor directly clutched at some driveline shaft, while the pneumatic starter is connected to the crankshaft of ICE [10]. It is briefed in the paper that the compressed air generated by the compressor during braking period is used for the ICE cranking by pneumatic starter, while no detailed analysis or simulation is given.

On the other hand, compressed air driven or pneumatic systems are already popular in most commercial vehicles, as a cost effective alternative to electric or hydraulic systems. A specified air compressor coupled with ICE crankshaft is almost always available, by which the compressed air is provided for air brake systems to boost the braking force actuation. In some comfort-oriented buses, the compressed air, stored in several tanks if necessary, is also used for air suspensions. If the air tank pressure is within a certain range, a pressure regulation valve is to deactivate the air charging, though the compressor may still keep rotating with the engine crankshaft.

In this context, if HPE is applied in commercial vehicles equipped with air brake system, the less expensive approach of regenerative braking, i.e. the out-of-cylinder approach, can be adopted. If the pneumatic compressor and starter are integrated as one single unit, i.e. compressor/expander unit (CEU), the complexities and additional cost may be further reduced. In addition to the pneumatic stop/start function, the compressed air recovered by the CEU may also work as the compressed air source for air brake or air suspension systems, thus reducing the energy consumption.

The rest of this paper is organized as follows. The next section details the concept of micro/mild pneumatic hybrid system with an integrated compressor/expander unit, aiming to achieve the pneumatic stop/start function. Then, for a case study, the models of CEU modes and an urban bus with a six-cylinder diesel engine are established. Driving cycle simulations are carried out to validate the concept. The final section gives the conclusion of this work and summarizes some future work.

PNEUMATIC HYBRID SYSTEM CONCEPT

Figure 1 shows the schematic diagram of the hybrid pneumatic engine with an integrated compressor/expander unit. As the core part of this concept, the proposed CEU based on the current on-board air compressor, works similarly to integrated starter/generator in mild hybrid electric vehicles. As shown in Figure 1, the CEU is coupled to engine flywheel with a coupler, which consists of two clutch subsystems with different ratios. The CEU has two different valve systems for compressor mode and expander mode, while the expander mode valve system is similar to normal reciprocating air motors.

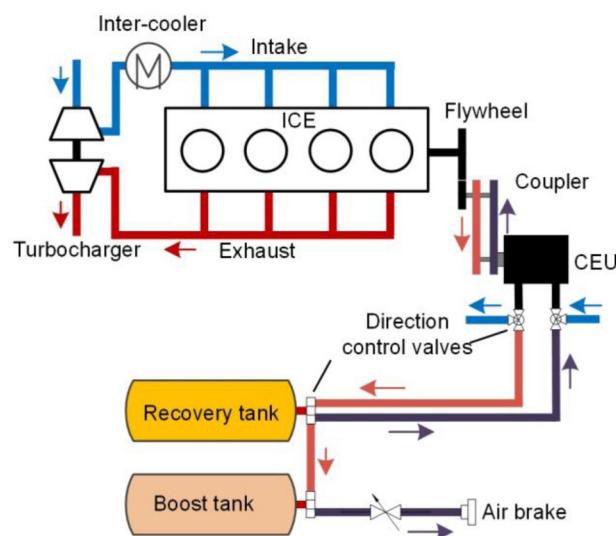


Figure 1. Schematic diagram of the hybrid pneumatic engine with the integrated compressor/expander unit.

In addition to the original compressed air tank for air boosted brake system (boost tank), a special recovery tank is added for braking energy recovery. The boost tank is only used for the air brake (not for energy recovery), while if its pressure is low it may be supplemented by the recovery tank or directly by starting the compressor. Note that air brake system on commercial vehicles usually needs several tanks to guarantee the brake safety, however, for simplicity, only one equivalent tank for brake boost is considered here.

During the vehicle deceleration, the fuel injection of the ICE is cut off, and the CEU works as the compressor mode. The low speed drive ratio (CEU shaft to flywheel, 1:1) is activated. This ensures that the compressor would not exceed its maximum

speed. The high pressure air produced by the compressor is charged to the recovery tank. The engine friction torque and compressor torque contribute to a part of the braking torque, while the deficit of braking torque is applied from conventional brakes. When the vehicle speed is very low, the clutch is released by the driver and the braking recovery process finishes.

When the vehicle is ready for re-starting, the CEU uses the compressed air of recovery tank to crank the ICE to a certain speed. At the expander mode, the high speed driving ratio is activated (CEU shaft to flywheel, 3:1), which increases the engine cranking torque from the expander. When the ICE cranking speed is high enough for starting, the fuel injection is activated as that in normal combustion mode.

Compared to the electric and hydraulic hybrid vehicles, this concept can be realized with slight modification, which include a two speed coupler, CEU, a recovery tank and some additional valves. The CEU is modified based on the original compressor on the vehicle. These are hopefully more cost effective than hydraulic motor/pump-accumulator or electric motor-battery combinations. As a rough estimate of the additional cost when applied in a typical urban bus vehicle, the proposed pneumatic system may cost about \$3,000, while the equivalent hydraulic approach may cost about \$10,000 and the electric hybrid approach may be even more expensive.

SYSTEM MODELING

To validate the proposed concept, a case study of an urban bus vehicle with six-cylinder diesel engine is carried out. In this section, the models of ICE and CEU (including compressor and expander modes) are presented and calculated. To evaluate the effect of overall fuel economy improvement due to both stop/start function and brake boost air tank pressure regulation, the air consumption of air brake boost system is also modeled. The entire vehicle model is modeled in Matlab/Simulink for driving cycle simulation and analysis with a quasi-static approach.

ICE Modeling

In the following quasi-static simulation of urban driving cycles, the ICE model is used to provide the fuel consumption in driving conditions, while the other performances such as emission are not considered yet. So only the fuel consumption and friction torque characteristics are needed. Table 1 gives some of the basic parameters of the studied engine, which is popularly adopted in urban bus market. Figures 2 and 3 present the bench tests results of the engine Brake Specific Fuel Consumption (BSFC) map and the friction torque with the fitted spline, respectively.

Table 1. ICE parameters.

Displaced volume	7140 cc
Stroke	130 mm
Bore	108 mm
Compression ratio	18:1
Number of Cylinders	6
Maximum torque	1100 Nm@1100r/min-1600r/min
Rated power	220 kW@2300r/min
Idle speed	900 r/min

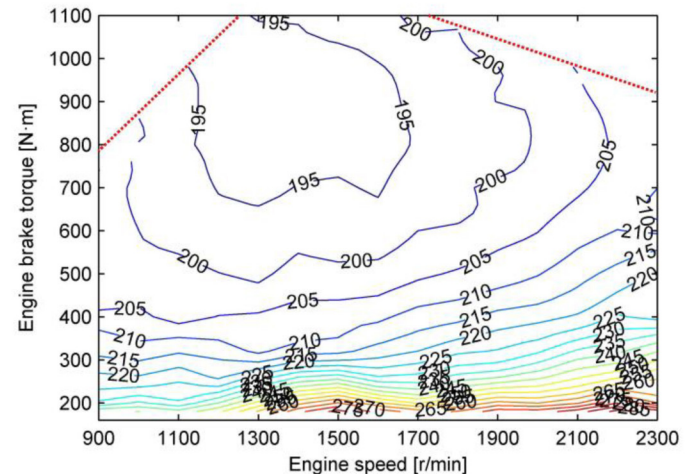


Figure 2. BSFC map from engine bench tests (unit: g/kWh).

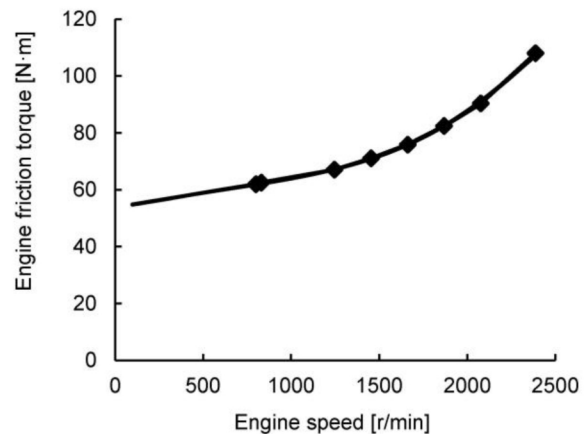


Figure 3. ICE friction torque from bench tests.

CEU Modeling

The CEU model describes the energy conversion between compressed air energy and mechanical energy, so the important details include the power, torque and conversion efficiencies. Both the compressor and expander modes of CEU work in a two-stroke style. Here, thermodynamics theory is used in modeling, and for simplification some parameters are assumed to be constants as listed in Table 2.