Pneumatic re-generation system in an electric car

Ziming Qi, Vivien Liang & David Hawkins

Abstract— As the clean energy car becomes the hot spot on the market, the electric car has been paid more attention. Although the weakness of the battery has recently been overcome (e.g. it has shorter charging time, higher power density, and longer life), in the current hybrid car, one more aspect concerned is efficiency. Efficiency of transformation from the energy of motion to electric energy is much lower than that from one type of mechanical energy to another type of mechanical energy. This paper is to present a novel design of pneumatic re-generation system hybrid in an electric car. First of all, in order to increase life of the battery, the battery isn't recharged during the car is running. It's only charged by the main power in the garage - It is called plug-in electric car. Secondly, the energy from the car's deceleration will be captured by a special gear box and be stored in the compressed air tanks. Thirdly, the energy stored will drive an air motor to supply supplemental power. Since this chain is a mechanical energy transformation, in theory, efficiency is higher than typical hybrid car. The experiment seems to get a satisfy result.

Keywords— electric car; hybrid car; compressed air

I. Introduction

An electric car has been paid an attention as its specification shows an acceptable top speed, a range of more than 160km (100 miles) on a full charge and a resealable price e.g. Nissan LEAF[1]. However, a question is still needed to be answered: Is it available for an urgent recharge when it shops on a bridge with a flat battery? Currently an "pure" electric car cannot have a satisfy answer since it is only able to offer a quick charger that can charge up to 80% of its full capacity in just under 30 minutes and charging at home through a 200V outlet is estimated to take approximately 8 hours. Therefore, some researches had suggested an office facility, equipped with renewable energy sources, where the users can recharge their plug-in electric vehicles, using the available renewable power [2]. Unfortunately such a facility does not offer an on-road solution, a hybrid car with an electric motor and an internal combustion engine (ICE) is still a consideration to reduce the opportunity of the issue of a flat battery on road. As such a hybrid car still need an ICE, which is a main concerned for its emission, a regenerative braking is an alternative solution. A regenerative braking is to reduce the fuel consumption.

Whilst most existing regenerative braking systems in a car transfer energy with generators and motors using batteries, an alternative regenerative braking system using a hydraulic drive with compressed air or nitrogen was displayed for a Ford

Tonka Truck [3]. A report showed this regenerative braking system had fuel savings during stop and go traffic up to 35% and reuse 80% of the braking energy. However, such a regenerative braking system cannot be commercialised in passenger's cars as it is not cost efficiency. It had to ensure the safety since a very high pressure is applied in this system.

This paper is to present a novel design of pneumatic re-generation system hybrid in an electric car. First of all, in order to increase life of the battery, the battery isn't recharged during the car is running. It's only charged by the main power in the garage - It is called plug-in electric car. Secondly, the energy from the car's deceleration will be captured by a special gear box and be stored in the compressed air tanks. Thirdly, the energy stored will drive an air motor to supply supplemental power. Since this chain is a mechanical energy transformation, in theory, efficiency is higher than typical hybrid car. Since the maximum working pressure is 120psi or 8bar, the cost for commercialised is at minimum level.

II. Design Method

The figure 1 shows a hypothetical indicator diagram for the compressor.

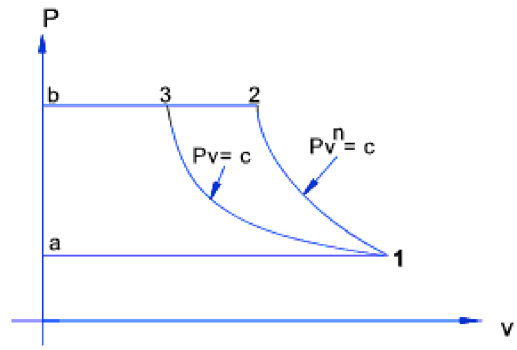

Figure 1 hypothetical indicator diagram for the compressor

As shown in Figure 1, from situation "a" to "1", the air is drawn into the cylinder on the suction stroke. From "1" to "2", the suction valve is closed and air is compressed according to the law

$$Pv^n = c \quad (1)$$

From "2" to "b", the delivery valve opens and air is delivered under pressure. From "b" to "a", the delivery valve closes and the suction valve opens.

Z. Qi is with Unitec Institute of Technology, Auckland, New Zealand. (e-mail: tqi@unitec.ac.nz)
V. Liang is with Cubic Defence New Zealand, Auckland, New Zealand. (e-mail: vivien.liang@cubic.com)
D. Hawkins is with Unitec Institute of Technology, Auckland, New Zealand. (e-mail: dhawkins@unitec.ac.nz)

The figure 2 shows the structure for the air power system.

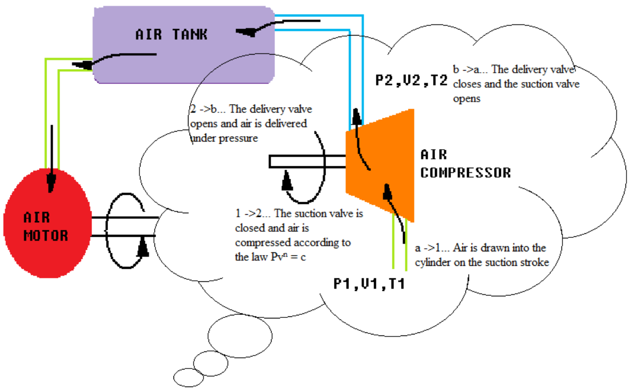

Figure 2 the designed system

As shown in Figure 2, the cloud callout shows the same process with the hypothetical indicator diagram for the compressor.

Assumptions in the system shown as Figure 1:

1. Steady operating conditions exist;
2. kinetic and potential energy changes are negligible;
3. The process is given to be adiabatic (transfer of heat across the system boundary)

Ideal gas the equation of state:

$$PV = RmT \quad (2)$$

Adiabatic process

$$pv^k = \text{constant} \quad (3)$$

Where k is Ratio c_p / c_v

k = 1.4, when it is Air, H_2, O_2, CO, NO, or HC_1.

k = 1.3, when it is CO_2, SO_2, H_2O, H_2S, N_2O, H_2S

Thus:

$$\frac{p_1}{p_2} = \left(\frac{v_2}{v_1}\right)^k \quad (3)$$

$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{k-1} \quad (3)\ (4)$$

$$\frac{T_1}{T_2} = \left(\frac{p_1}{p_2}\right)^{\frac{k-1}{k}} \quad (5)$$

The theoretical work done on the air per cycle is the area enclosed by [a-1-2-b- a] which equals

$$W = \int_{V_2}^{V_1} pdV = \int_{V_2}^{V_1} \frac{C}{V^K} dV = C \cdot \frac{1}{1-K}(V_1^{1-K} - V_2^{1-K})$$

$$= \frac{1}{1-K}(V_1^{1-K} \cdot p_1 V_1^K - V_2^{1-K} \cdot p_2 V_2^K) = \frac{1}{K-1}(p_2 V_2 - p_1 V_1)$$

$$W = \frac{K}{K-1} p_1 V_1 [(\frac{p_2}{p_1})^{\frac{K-1}{K}} - 1] \quad (6)$$

$$T_2 = T_1 (\frac{p_2}{p_1})^{\frac{K-1}{K}} = T_1 \varepsilon^{\frac{K-1}{K}} \quad (7)$$

When the golf cart goes downhill, the power is switched off, and the air compressor is turned on and is driven by the running gear. The work done on the air per cycle is

$$W = \frac{K}{K-1} p_1 V_1 [(\frac{p_2}{p_1})^{\frac{K-1}{K}} - 1] \quad (8)$$

In this period, the work done on the cart by the friction is

$$W = f F \cos\theta S \quad (9)$$

Where is Fiction coefficient, F is Weight of the cart, θ is Degree of the hill, S is the distance the cart runs.

Comparing these two works, we can get the efficiency of the transmission.

III. Experiments

A typical electric golf cart has an electric motor and a battery. It is not only used in golf courts but also many workplaces e.g. railway stations and airports. A typical golf cart “Club car” is employed in this project as showed in Figure 3. Keeping the existing electric motor and battery (also all other equipment) in golf cart so that it can be operated as usual, this golf cart was Installed an air compressor and an air motor. A gear box in a golf cart was designed to enable additional power that can be transmitted or received from/to the axis in a golf cart. A clutch to switch the gearbox drive to an air compressor to store energy from the axis or switch the gearbox drive to an air motor to release energy to the axis. Figure 4 shows an overview of a modified golf cart. The system assemble is located at rear part.

Figure 3 overview - the system assemble at the rear part of the golf cart

As showed in Figure 5, there are 4 major parts in the compressor air system: A compressor tank, a clutch with belt, an air compressor and an air motor.

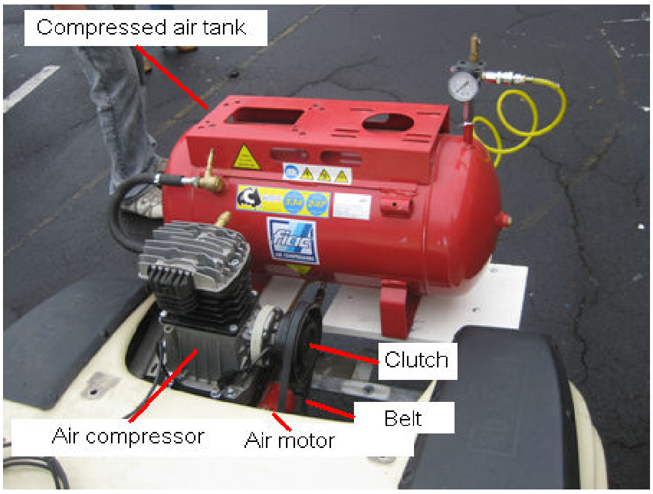

Figure 4 the compressed air system

The air compressor (as in Figure 5) is to regenerate the energy of motion (when the golf cart is at downhill or shopping). The compressed air tank is to store energy from the motion of the golf cart.

An air motor is to output the stored energy in the compressed air tank via the belt to the gear box to provide an additional assistant to the electric motor when it is needed.

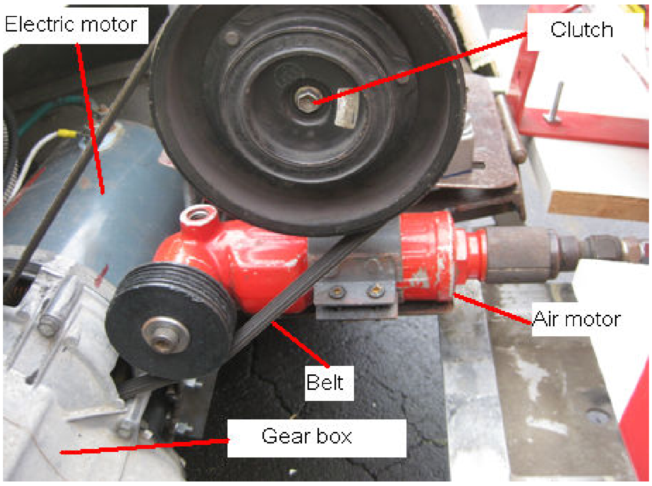

Figure 5 Power transmitting unit

Condition of the experiment:

1. Golf cart: Electric motor:4kw, 48 volt;
   Max speed: 35km/h
   Net weight: 320 kg
2. Air compressor:
3. Air tank: 50 litres
4. Air motor:

Procedure of the experiment:

1. Fully power the cart by electric motor then turn off the power to let it free running;
2. Fully power the cart by electric motor then turn off the power, at the same time switch on the air compressor;
3. Fully power the cart by electric motor then turn off the power, at the same time switch on the air motor.
4. Power the cart by air motor from still condition.

The main points of the experiment:

1. Every time, from the same position “A” to fully power the cart by electric motor ;

Every time, at the same position “B” to turn off the electric motor and at the same time to switch on the air compressor or air motor.

The regenerative rate (RG) can be calculated

$$RG = \frac{L_{input} / P_{up}}{L_{output} / P_{down}} \qquad (10)$$

Where L_{input} is the travel distance of golf cart lost, which is caused by the tank receiving compressed air. L_{output} is the travel distance of the golf cart using the compressed air from the tank. P_{up} is the level of arising pressure in PSI, which means receiving energy to the tank. P_{down} is the level of falling pressure in PSI, which means outputting energy from the tank.

A. Road condition 1:

There is a curve in a gentle downhill (in 5°).as shown in Figure 9.

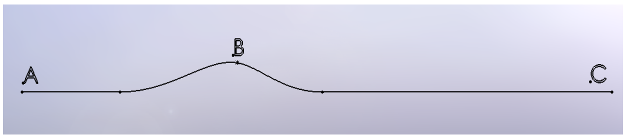

Figure 6 there are a curve in a downhill

Procedure 1: Fully power the cart by electric motor then turn off the power to let it free running. Distance between point B and C is 40 meters.

Procedure 2: Fully power the cart by electric motor then turn off the power, at the same time switch on the air compressor. The results are as Table 1. It means the tank receives the motion energy of average of 20 meters by increasing 4 PSI in pressure.

Procedure 3: Fully power the cart by electric motor then turn off the power, at the same time switch on the air motor. The results are as Table 2. It means that the golf cart moves 10 meters over 40 meters spends average of 10 PSI in pressure.

Table 1

	Air pressure at point B	Air pressure at point C	Distance between B and C
1	56psi	60psi	20 metres
2	59psi	63psi	20metres
3	62psi	66psi	19metres
4	64psi	69psi	19metres
5	68psi	72psi	19metres

Table 2

	Air pressure at point B	Air pressure at point C	Distance between B and C
1	68psi	58psi	50 metres
2	74psi	63psi	52metres

Procedure 4: Power the cart by air motor from still condition. The results are as Table 3. It means that the compressed air drove the golf cart 2 meters by spending 1 PSI in this test.

Table 3

	Air pressure at point B	Air pressure at point C	Distance between B and C
1	64psi	53psi	26 metres
2	52psi	33psi	32metres

Comparing Table 1 and 2, there is a regenerative rate is 80%.

B. Road condition 2:

The test was in a flat open road with a gentle uphill (less than 5°).

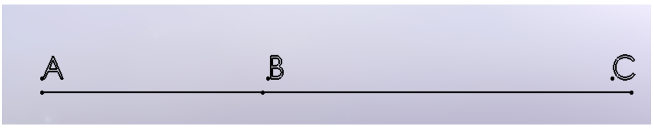

Figure 7 Test in uphill

Procedure 1: Fully power the cart by electric motor then turn off the power to let it free running. The distance between point B and C is12 meters.

Procedure 2: Fully power the cart by electric motor then turn off the power, at the same time switch on the air compressor. The results are as Table 4. It means the tank receives the motion energy of average of 6 meters by increasing 1 PSI in pressure.

Table 4

	Air pressure at point B	Air pressure at point C	Distance between B and C
1	51psi	51psi	5metres
2	60psi	61psi	7.8metres
3	60psi	62psi	6.5metres
4	61psi	62psi	6.6metres
5	62psi	64psi	6.4metres
6	64psi	64psi	6.2metres
7	64psi	64psi	6.1metres
8	64psi	65psi	6.1metres
9	65psi	66psi	6.1metres
10	66psi	67psi	6.1metres
11	67psi	68psi	6.1metres
12	68psi	69psi	5.8metres
13	69psi	69.5psi	6metres
14	69.5psi	70psi	6.1metres
15	70psi	70psi	6.1metres

Procedure 3: Fully power the cart by electric motor then turn off the power, at the same time switch on the air motor. The results are showed as Table 5. It means that the golf cart moves 6 meters over 12 meters spends average of 20 PSI in pressure.

Table 5

	Air pressure at point B	Air pressure at point C	Distance between B and C	Air pressure at point C after stop a while
1	60psi	49psi	18 metres	
1	70psi	54psi	15.7 metres	57psi
2	138psi	103psi	24.3metres	106psi

Comparing Table 4 and 5, there is a regenerative rate is 5%.

As the road condition is not flat and uphill, an extra procedure was arranged:

Repeat procedure 1: Fully power the cart by electric motor then turn off the power to let it free running. Distance between point B and C is11.2 meters and the distance between point C and B is19 meters. It means from B to C is uphill.

Repeat procedure 2: Fully power the cart by electric motor then turn off the power, at the same time switch on the air compressor. As showed in Table 6, when it is uphill, the tank receives the motion energy of average of 6 meters by increasing 1 PSI in pressure; when it is downhill, the tank receives the motion energy of average of 9 meters by increasing 1 PSI in pressure.

Table 6

	Go from B to C				Go from C to B		
	Air pressure at point B	Air pressure at point C	Distance between B and C (meters)		Air pressure at point C	Air pressure at point B	Distance between C and B (meters)
1	50psi	50psi	7		46psi	49psi	9.9
2	49psi	52psi	5.9		52psi	53psi	8.6
3	53psi	54psi	7		54psi	55psi	7.5
4	55psi	56psi	6.2		56psi	57psi	9

Repeat procedure 3: Fully power the cart by electric motor then turn off the power, at the same time switch on the air motor. The results are showed as Table 7. When it is uphill, the golf cart moves 6 meters more over 12 meters spends average of 14 PSI in pressure. When it is downhill, the golf cart moves 20 meters more over 29 meters spends average of 18 PSI in pressure.

Comparing Table 6 and 7, when it is up hill, there is a regenerative rate is 7%. And when it is up hill, there is a regenerative rate is 12%.

Table 7

	Go from B to C				Go from C to B		
	Air pressuer at point B	Air pressure at point C	Distance between B and C (meters)		Air pressuer at point C	Air pressure at point B	Distance between C and B (meters)
1	69psi	55psi	16.2		70psi	52psi	29.5
2	70psi	56psi	16.2		70psi	52psi	29

C. Road condition 3:

A new road condition as shown in Figure 8, fully power the cart by electric motor then turn off the power, at the same time switch on the air motor. The results are showed as Table 8. When it is uphill, the golf cart moves 26 meters spending average of 20 PSI in pressure; when it is downhill, the golf cart moves 27 meters spending average of 18 PSI in pressure.

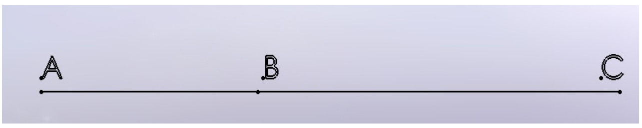

Figure 8

Procedure 3:

Table 8

	Go from B to C				Go from C to B		
	Air pressure at point B	Air pressure at point C	Distance between B and C (meters)		Air pressure at point C	Air pressure at point B	Distance between C and B (meters)
1	70psi	50psi	24.9		70psi	52psi	27
2	70psi	50psi	27		70psi	52psi	26
3	70psi	52psi	28		70psi	52psi	28

The test started at 10:54 last Monday. Air pressure increased from 0 to 100psi in 2 minutes. Temperature changed from 19deg to 44deg. When the pressure dropped to 50psi, temperature was 38deg.

When the pressure was 50psi, we started the motor to drive the compressor to increase air pressure to 60psi then 70psi, the relevant temperature was 34deg, 38deg and 44deg.

We repeated the same experiment for other three times: the air pressure increased from 50psi to 70psi, the relevant temperature changed from 32deg to 44deg; 39deg to 48deg and 39deg and 48deg.

Concluding from the records, when the air pressure increased from 50psi to 70psi, the temperature difference is about 9~10deg.

IV. Conclusion and Discussion

This research had confirmed that the compressed air in an electric car is suitable for regenerating energy from motion and being used as additional power source. Additional finding is that the regenerative rate can be between 5%-12% in a normal road condition. While it is in downhill, the regenerative rate reaches as much as 80%.

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