



Received: 14 June 2016  
Accepted: 22 October 2016  
First Published: 27 October 2016

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Reviewing Editor:  
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## PRODUCTION & MANUFACTURING | RESEARCH ARTICLE

# Test platform design for regenerative braking of hub-motor

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**Abstract:** Electric brake experiment of hub-motor is preliminary basis of the regeneration braking control strategy. A regenerative braking test bench of hub-motor is designed in which the test and control system is developed based on Labview and NI virtual instrument. The physical structure, signal acquisition hardware and test system principle of the bench are introduced. The bench can test torque and speed of the hub-motor, on which the electric brake experiment and etc. can be done. Through the unloaded glide and electric brake experiments, the results show that the design of the bench is reasonable and control modes of the test and control system is feasible. Furthermore, the test bench can provide important references for regeneration braking control strategy and motor performance tests.

**Subjects:** Manufacturing Engineering; Transport & Vehicle Engineering; Electrical & Electronic Engineering

**Keywords:** regenerative braking; hub-motor; electric vehicle; Labview

### 1. Introduction

Although the electric vehicle efficiency of regeneration braking energy recovery is yet to be improved, it has a huge application market. All car manufacturers have begun to pay attention to the

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### PUBLIC INTEREST STATEMENT

The electric vehicle market increased fast, and a new direction is four-wheel-driven electronic vehicle using hub-motor. We researched how the hub-motor driven vehicle can use the energy of vehicle motion when it's braking. We designed a system according to relevant experiment by the theoretical model.

This equipment for energy feedback of electric vehicle must coordinate with the mechanic brake system, or it will make the vehicle unstable while braking. It should control the regenerative braking force and mechanic braking force. This work need support from some fundamental experiment data.

So, in this paper, we designed an experiment platform to measure the parameters when regenerative braking and analysis the affections of the energy feedback to the brake force, and the braking distance and other relevant parameters. This research will supply test model and fundamental experiment method about regenerative braking of electronic vehicle driven by hub-motors.

energy saving value of car regeneration braking (Fu, Zhang, & Yan, 2014), and the regeneration braking experiment has become one of the important branches of electric vehicle performance test (Sui, Wang, Li, Zhang, & Jianbo, 2011). On the other hand, hub-motors begin to get more application to automobile driving.

According to the direction of the power transmission, hub-motor drive cars can be divided into front-wheel drive, rear-wheel drive and four-wheel drive (Qian, Zhao, & Gao, 2002). The hub-motor four-wheel drive cars are more and more popular due to less mechanical wear, power loss and simple transmission (Qiu, Lei, Qi, & Dong, 2011; Qiu, Liang, Qi, & Qin, 2012). So, the study of regeneration braking on four-wheel-drive cars with hub-motor has much great significance.

In the aspect of regeneration braking experiment of electric vehicle, researches based on pure electric vehicle experiment bench driven by centralized control motor was reported and they studied the experimental steps, carried out the real vehicle experiment verification (Fei, Cui, & Liu, 2014). But the regeneration braking experiment of four-wheel-independent-drive cars with hub-motor requires further study. At the same time, the regeneration braking experiment of four-wheel-independent-drive cars with hub-motor focus on the performance of the hub-motors because the design of electric vehicle drive system establishes on the motor characteristic curve, although there are not unified standards and test methods to the hub-motors of electric vehicle (He, Xiaojiang, Sun, & Zhang, 2006).

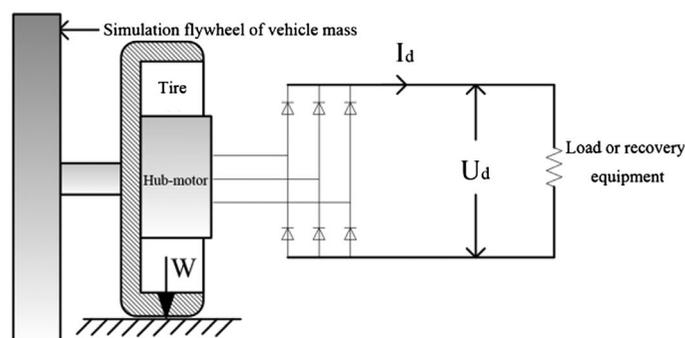
Therefore, the experimental bench of hub-motor regeneration braking studied in this paper can test the performances of hub-motors and roller, such as rotating speed, torque, voltage, current, etc. Also, the bench can make the experiment of regeneration braking to verify the regeneration braking control strategy. To simplify the measurement and control system, taking National instrument (NI) virtual system as the development platform, the experimental bench develops the measurement and control system based on Labview, which has friendly interface, comprehensive functions, simple operation, and easy maintenance. We mainly make regeneration braking experiments of hub-motors as an example for illustrating in this paper.

## 2. Experimental model

A DC brushless hub-motor is adopted as the drive motor. According to the structure of the electric vehicle, the model of braking energy feedback of the electric vehicle can be simplified as shown in Figure 1.

During braking, the mass inertia of the car goes forward, which drives hub-motor to generate electricity. If the energy feedback is needed, it will be transmitted to the energy storage device after full-wave rectification. According to the theory of vehicle driving, the braking torque  $T_b$  acted on tires when car brakes includes the resisting moment  $T_f$  produced by rolling resistance of pavement to tires and the electromagnetic brake torque  $T_e$  produced by the coil current in energy feedback. Assuming  $f$  as attachment coefficient,  $r$  as the radius of the tire, and  $W$  as vehicle weight, under the condition of horizontal road and medium-low speed, regardless of the wind resistance, gradient resistance and mechanical braking torque:

Figure 1. Simplified model of braking recovery of hub-motor.



$$T_b = T_f + T_e = fWr + T_e \tag{1}$$

According to the motor electromagnetic theory and the principle of three-phase alternating current, under the condition of power generation, assuming  $I_\phi$  as the effective value of motor coil phase current,  $I_d$  as average value of load or feedback current after full-wave rectification:

$$T_e = C_\mu \varphi_m I_\phi = \pi / \sqrt{6} C_\mu \varphi_m I_d \tag{2}$$

Assuming  $J$  as equivalent rotational inertia of car quality,  $\omega$  as angular velocity,  $v$  as speed,  $r$  as wheel radius, the dynamics equation while braking is as follows:

$$T_b = J \frac{d\omega}{dt} = \frac{J}{r} \frac{dv}{dt} \tag{3}$$

Substituting (1) and (2) to (3), then:

$$fWr + \pi / \sqrt{6} C_\mu \varphi_m I_d = \frac{J}{r} \frac{dv}{dt} \tag{4}$$

So, in the regeneration braking simulation experiment, we need to simulate the vehicle weight  $W$ , pavement performance  $f$ , vehicle body equivalent rotational inertia  $J$  and brake feedback current  $I_d$ , and analyze the influence of  $I_d$  on vehicle deceleration  $dv/dt$  and velocity  $v$ . To realize those, the experimental bench is designed in this paper.

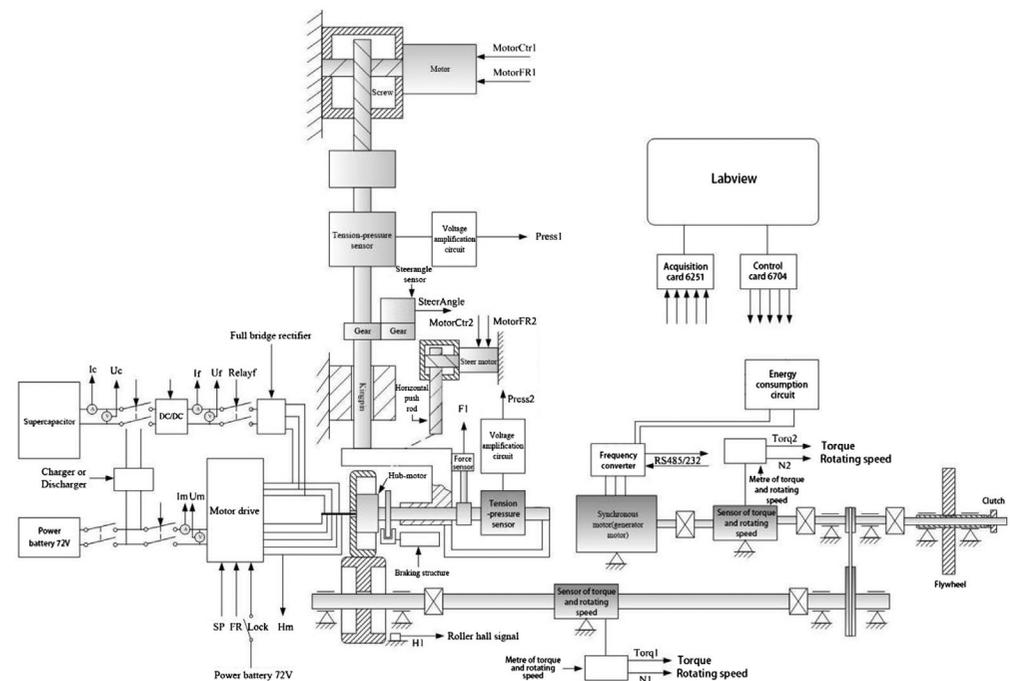
### 3. The structure and working principle of the experimental bench

The experimental bench includes the mechanical structure, signal acquisition hardware and measurement and control system.

#### 3.1. The entity structure of the bench

As shown in Figure 2, the entity structure of the bench is mainly composed of five parts, namely the driving wheel device, vertical loading device, road simulator, car body inertia simulator, regeneration braking actuator.

Figure 2. Structure of experimental bench.



Driving wheel device is the center of the bench, including the hub-motor of YKSX 72 V-5 KW DC brushless and tire of 165/70 R13.

Bench vertical loading device drives the screw to move up and down by a motor, and drives the kingpin, cantilever and motor shaft to move to change the pressure between tire and roller. There is a pressure sensor in the kingpin for measuring the load.

Road simulator covers tiles of different materials on the roller surface touched with tire to simulate road surface of different attachment coefficients through adding oil or water on the tiles.

Car body inertia simulator mainly includes speeding-up belt wheel whose speed ratio is 1:3, flywheel which simulates rotational inertia of 1/4 vehicle and the clutch. If the flywheel is not needed, such as simulating braking energy feedback on the long downhill road, the clutch can be released.

Regeneration braking actuator mainly includes the synchronous motor and frequency converter. In the vehicle braking energy feedback experiment, the frequency converter controls synchronous motor which drives the hub-motor rotation to simulate braking initial velocities and torques under different conditions. In the emergency braking and frequent braking experiment, the frequency converter runs in speed mode to simulate various initial velocities. In the long downhill braking energy feedback experiment, the frequency converter runs in torque mode to simulate the component force of car body's gravity on the slope.

### 3.2. Signal acquisition hardware of bench

According to the theoretical analysis above, in the experiment, we need to analyze the signal of car body acceleration obtained by the wheel speed differentia and the rectifier current under the condition of hub-motor's power generation state. Meanwhile, the braking distance needed in experiment requires measurement for roller's turned distance.

For further analysis, in the experiment we collect the wheel rotating speed signal  $n_1$ , flywheel Hall pulse signal  $H_1$  for analysis of braking distance, current signal  $I_d$  of motor power rectifier output, and the vertical load  $W$ . We also collect signals such as the output torque of motor, the input and output torque and the rotating speed of roller, rectified voltage, etc.

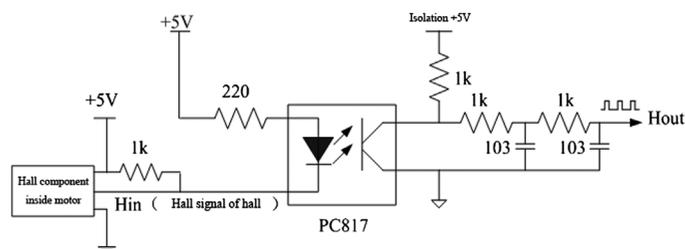
#### 3.2.1. Acquisition hardware of the motor's rotate speed signal $n_1$

The hub-motor is a DC brushless motor whose rotating speed is acquired from the Hall signal. The motor itself has three Hall signals to determine the position of the rotor, and we can use them as the signals of wheel rotating speed. Because the motor driver doesn't work and the power supply of Hall signal is off in the brake experiment, we need to supply +5 V power for the Hall device inside the motor. Sampling circuit is as shown in Figure 3.

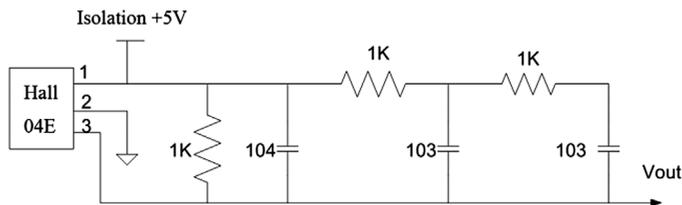
#### 3.2.2. Acquisition hardware of the flywheel Hall pulse signal $H_1$

In order to measure the brake distance during braking more accurately, we need to measure the turned position of roller during braking. Therefore, we install eight magnetic steel pieces on the flywheel around the center equidistantly to test through the Hall device. The test circuit is as shown in Figure 4.

**Figure 3. Acquisition hardware of motor rotating speed signal.**



**Figure 4. Acquisition hardware of flywheel hall signal.**



The output current of Hall element 04E is converted to a voltage signal through a 1 k resistor, and the voltage signal is sent to the counter channel of virtual instrument through a low-pass filtering.

### 3.2.3. Acquisition hardware of the rectifier output current signal $I_d$ during hub-motor's power generation

A perforation magnetic balance type Hall current sensor SCB11 is adopted to detect the current because of the large current during braking energy feedback.

### 3.2.4. Acquisition hardware of the vertical load signal $W$

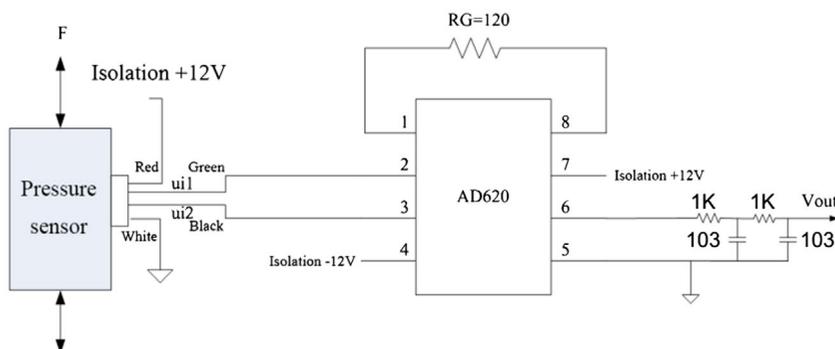
The tension-pull pressure sensor BLR1 of 300 kg is adopted for vertical load measurement, inside of which is bridge circuit. The sensitivity of the sensor is 1.098 mv/kg, and the signals need to be amplified. The instrumentation amplifier AD620 is used in this experiment. The amplification gain is 412.67 and the adjustment resistance of 120  $\Omega$  is chosen. Acquisition circuit is as shown in Figure 5.

## 3.3. Bench measurement and control system based on virtual instrument

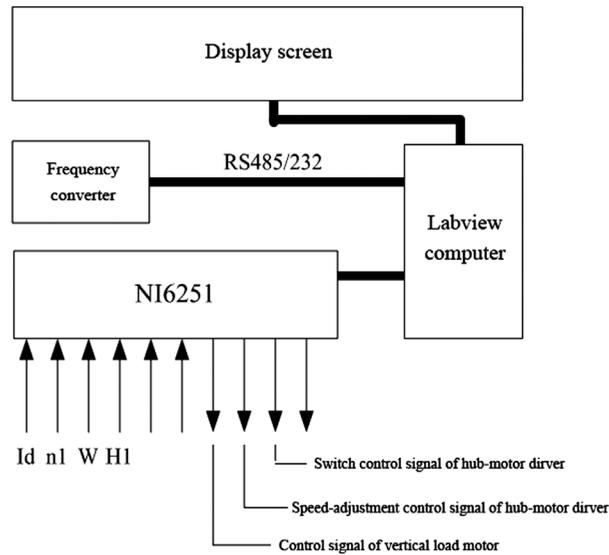
We adopt virtual instrument system of National instrument as bench measurement and control system. All collected physical signals acquired by NI's PCI card NI6251 are processed by Labview software, and displayed on the computer. At the same time, the control signals, such as controlling frequency converter, the hub-motor driver, the vertical pressurization motor, are output by NI's PCI card NI6704 and RS232. The measurement and control system is as shown in Figure 6.

NI6251 has 16 analog input channels, 2 analog output channels and 24 digital I/O channels and digital channels include 2 channels with counter function. Current  $I_d$ , vehicle weight  $W$  are acquired through analog channels and converted to voltage signals. For the convenience of calculating rotating speed and driving distance, the rotating speed  $n_1$  and flywheel Hall signal H1 are acquired through digital I/O channels with counter function. In the experiment, the control system, such as adjusting the vertical load, switching the motor, changing the motor speed, are all digital signals, which are controlled by digital output channels directly.

**Figure 5. Acquisition hardware of vertical load signal.**



**Figure 6. Measurement and control system based on Labview.**



Frequency converter should be able to adjust speed of motor used to drag. Synchronous motor frequency converter is equipped with RS485 interface, while NI devices only have RS232 interface, so the motor used to drag is controlled by NI's instruction to frequency converter through RS232 to RS485 data line.

## 4. Experiments

### 4.1. Experimental scheme

The speed of electric wheel is increased to a certain value (67 km/h) and then the hub-motor is controlled under power generation condition to make electric braking experiment. The vehicle speed and braking deceleration are calculated based on the data of roller rotating speed, driving distance, and feedback current. To analyze the brake performance of electric braking, we compared the parameters of braking time, braking distance and braking deceleration with those in no-load slide experiment.

### 4.2. Experimental results

The hub-motor carries out electric braking as a generator, while the output current is consumed through resistors. No-load slide carries out braking by roller friction without slippage between tire and roller. This vehicle speed is obtained from the formula  $v = 2\pi rn$ , and deceleration is calculated by  $a = \Delta v / \Delta t$ , in which  $\Delta t$  is 0.2 s,  $\Delta v$  is the speed difference between the two time points.

We can see from Figures 7 and 8, under the no-load slide condition, the speed of electric wheel slows down evenly because the wheel is only affected by rolling resistance. The value of the decline is stable at about  $0.45 \text{ m/s}^2$  and there almost appears a straight line in the figure. Under the electric braking condition, the driving distance and time shorten about a half, and the faster the vehicle speed is, the more obvious the braking effect is. The biggest deceleration is up to  $1.53 \text{ m/s}^2$ .

As shown in Figure 9, we can draw scatterplot of feedback current and deceleration, and then generate the function of deceleration and feedback current using least square method to get the fitting relation expression:  $a = 0.0185I + 0.3767$ . It can be obtained according to this formula, how much current the car should be provided under a certain value of decelerating, which becomes a kind of control scheme.

Figure 7. Contrast of vehicle speed under no-load and braking.

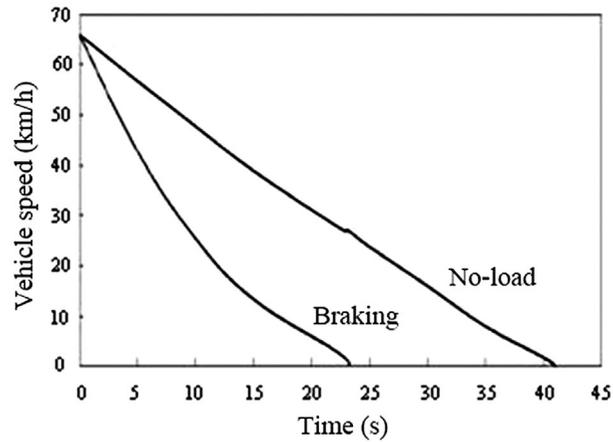


Figure 8. Contrast of driving distance under no-load and braking.

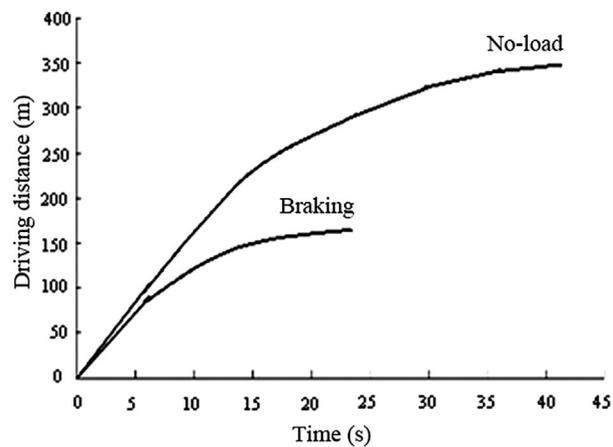
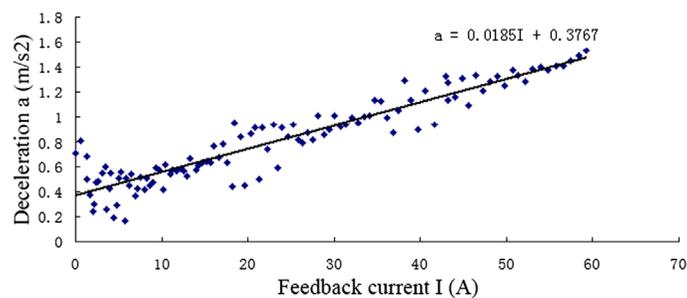


Figure 9. Function of deceleration and feedback current.



### 5. Conclusions

These experiments can help us to research the regeneration braking. The first one shows that the rolling resistance is stable on our experiment conditions, and also gives the method to evaluate the parameter when we set the control model. The second and third can help us evaluate the influence of energy feedback to the braking efficiency, and let us can predicate the braking deceleration with the running data. These data is the fundamental of regeneration braking studying and the control system model.

The experiment bench can also test hub-motor's performances besides hub-motor's regeneration braking experiment. Based on virtual instrument Labview and NI data acquisition cards, on the physical architecture of hub-motor regeneration braking experiment bench, we designed hardware system and software environment of its measurement and control system, and verified the architecture rationality

of the experiment bench and the control feasibility of the measurement and control system. Experimental results of no-load slide and electric braking show that, the experiment bench design is reasonable, the operation of measurement and control system is stable, which can provide an important reference basis for the future study on the regeneration braking control strategy and electrical performance tests.

#### Funding

This paper is supported by The national Natural Science Fund [grant number 51175050], Guangdong Provincial Natural Science Fund [grant number S2013010013931] and Shenzhen science and Technology Development Fund Project [grant number CXZZ20120617143011586].

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#### Citation information

Cite this article as: Test platform design for regenerative braking of hub-motor, Chengwei Han, Ziming Qi & Hao Qiu, *Cogent Engineering* (2016), 3: 1253232.

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