Research Article

Research into the Effect of Supercapacitor Terminal Voltage on Regenerative Suspension Energy-Regeneration and Dynamic Performance

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To study the effect of supercapacitor initial terminal voltage on the regenerative and semiactive suspension energy-regeneration and dynamic performance, firstly, the relationship between supercapacitor terminal voltage and linear motor electromagnetic damping force and that between supercapacitor terminal voltage and recycled energy by the supercapacitor in one single switching period were both analyzed. The result shows that the linear motor electromagnetic damping force is irrelevant to the supercapacitor terminal voltage, and the recycled energy by the supercapacitor reaches the maximum when initial terminal voltage of the supercapacitor equals output terminal voltage of the linear motor. Then, performances of system dynamics and energy-regeneration were studied as the supercapacitor initial terminal voltage varied in situations of B level and C level road. The result showed that recycled energy by the supercapacitor increased at first and then decreased while the dynamic performance had no obvious change. On the basis of previous study, a mode-switching control strategy of supercapacitor for the regenerative and semiactive suspension system was proposed, and the mode-switching rule was built. According to simulation and experiment results, the system energy-regeneration efficiency can be increased by utilizing the control strategy without influencing suspension dynamic performance, which is highly valuable to practical engineering.

1. Introduction

Vibration impact of the vehicle body is converted into thermal energy and then dissipated by dampers, which greatly reduces utilization of energy generated by the engine [1–4]. Kinetic and potential energy of the vehicle body in vertical direction can be converted into electrical energy by power generation devices and then is utilized in the regenerative suspension system [5–9].

The control and energy storage circuit of the regenerative suspension system has been designed and researched by many scholars [10–15]. In researches of Tsinghua University and State University of New York, recycled energy in the electromagnetic and semiactive suspension was stored into the battery through a Buck-Boost switching converter, and the system activation force was adjusted by changing switching signal of the converter. Chen et al. have researched

into the energy management system of the intelligent suspension [16–18]. A charge-discharge device was utilized in the research, which transferred the extra energy stored in the supercapacitor into a battery. However, effects of the charge-discharge device on energy-regeneration efficiency and dynamic performance were not analyzed.

A DC-DC converter can realize an effective control of the electromotor winding current, which has been applied to the regenerative suspension system to control the activation force, and serves as the path of energy output as well [18–21]. The effect of a DC-DC converter on the suspension system dynamics and energy-regeneration efficiency, which had been often neglected, was analyzed in this paper. In addition, a mode-switching control strategy of supercapacitor for the regenerative and semiactive suspension system was proposed, which increased energy-regeneration efficiency on the premise of good suspension dynamic performance.

FIGURE 1

2. Analysis of DC_DC Converter Operation Performance

To realize semiactive control of the system and energy-regeneration, the resistance of a traditional Boost circuit was replaced by a supercapacitor. The new topological structure is shown in Figure 1(a). u_M is output terminal voltage of the linear motor which has been rectified by a rectifier.

Components of the circuit are assumed to be ideal; namely, conduction resistances of the diode and the MOS pipeline are both zero. The switching period is defined as $[-DT, (1-D)T]$. T is period of the switching signal and D is duty ratio of the switching period.

When $t \in [-DT, 0]$, as is shown in Figure 1(b), the MOS pipeline Q is conducted, and u_M is given by Kirchhoff Voltage Law (KVL):

$$u_M = L \frac{di_1}{dt}. \quad (1)$$

From (1), i_1 can be calculated as

$$i_1 = \frac{u_M}{L} (t + DT) + I_0. \quad (2)$$

I_0 is current of the inductor when $t = -DT$, and i_1 is current of the inductor when $t \in [-DT, 0]$.

When $t \in [0, (1-D)T]$, the MOS pipeline Q is cutoff, and as is shown in Figure 1(c), the inductor L and the power source u_M both charge the supercapacitor. At this point

$$u_M + L \frac{di_2}{dt} = u_0 + u_C, \quad (3)$$

$$i_2 = C \frac{du_C}{dt}.$$

u_0 is initial terminal voltage of the supercapacitor when $t = 0$. u_C is an increment of the supercapacitor terminal voltage during the time of $[0, (1-D)T]$, and i_2 is current of the inductor during $t \in [-DT, 0]$.

It can be calculated from (3) that

$$u_C = k_1 e^{t/\tau} + k_2 e^{-t/\tau} + u_M - u_0. \quad (4)$$

Further, from (3), i_2 is given as

$$i_2 = \sqrt{\frac{C}{L}} (k_1 e^{t/\tau} - k_2 e^{-t/\tau}). \quad (5)$$

In (5), $\tau = \sqrt{LC}$, k_1 , and k_2 are undetermined coefficients.

When $t = 0$, $u_C = 0$, and $i_1 = i_2$, thus

$$k_1 = \frac{u_0}{2} - \frac{u_M}{2} \left(1 - \frac{DT}{\tau}\right) + \frac{I_0}{2} \sqrt{\frac{L}{C}}, \quad (6)$$

$$k_2 = \frac{u_0}{2} - \frac{u_M}{2} \left(1 + \frac{DT}{\tau}\right) - \frac{I_0}{2} \sqrt{\frac{L}{C}}.$$

Current in the circuit has a shape of triangular wave; thus mean value and virtual value of the current are equal. The mean value, as well as the virtual value, can be given as

$$I = \frac{DT u_M}{2L} + I_0. \quad (7)$$

The output electromagnetic damping force of the linear motor is

$$F = k_i \cdot I = \frac{k_i DT u_M}{2L} + k_i I_0. \quad (8)$$

In (8), k_i is electromagnetic damping coefficient of the linear motor. It can be seen from (8) that output electromagnetic damping force of the linear motor, which is irrelevant to initial terminal voltage of the supercapacitor, is proportional to duty ratio of the switching signal. Further, it can be inferred that the initial terminal voltage of the supercapacitor does not influence the suspension dynamics.

The recycled energy W in one period is

$$W = \frac{1}{2} C [(u_0 + u_C)^2 - u_0^2] = \frac{1}{2} C (u_C^2 + 2u_C u_0). \quad (9)$$

By derivation of u_0 in (9), it can be seen that W reaches the maximum when

$$u_0 = \frac{u_M (e^{t/\tau} + e^{-t/\tau})}{e^{t/\tau} + e^{-t/\tau} - 2}. \quad (10)$$

$W_{\max}$ is given as

$$W_{\max} = \frac{u_M^2 (e^{2t/\tau} - e^{-2t/\tau})}{4 (e^{t/\tau} + e^{-t/\tau} - 2)^2} + \frac{u_M^2 (e^{t/\tau} + e^{-t/\tau})^2}{e^{t/\tau} + e^{-t/\tau} - 2} - \frac{u_M (e^{t/\tau} + e^{-t/\tau})}{e^{t/\tau} + e^{-t/\tau} - 2} [(\lambda_1 + \lambda_2) + \lambda_1 e^{2t/\tau} + \lambda_2 e^{-2t/\tau}] + \lambda_1^2 e^{2t/\tau} + \lambda_2^2 e^{-2t/\tau} + 2\lambda_1 \lambda_2 - 2u_M (\lambda_1 e^{t/\tau} + \lambda_2 e^{-t/\tau}) + u_M^2. \quad (11)$$

TABLE 1: Simulation parameters.

Parameter	Unit	Parameter value
Sprung mass m_2	kg	317.5
Unsprung mass m_1	kg	45.4
Tire stiffness coefficient k_t	N·m ⁻¹	192000
Spring stiffness coefficient k	N·m ⁻¹	22000
Damping coefficient of the original damper c_0	N·s·m ⁻¹	1500
Back EMF coefficient k_e	V·s·m ⁻¹	62.6
Electromagnetic damping coefficient k_i	N·A ⁻¹	77.9

In the above equation,

$$\begin{aligned}\lambda_1 &= \frac{u_M}{2} \left(1 - \frac{DT}{\tau} \right) - \frac{I_0}{2} \sqrt{\frac{L}{C}}, \\ \lambda_2 &= \frac{u_M}{2} \left(1 + \frac{DT}{\tau} \right) + \frac{I_0}{2} \sqrt{\frac{L}{C}}.\end{aligned}\quad (12)$$

The selected switching ratio f of circuit design is 20 KHz and $t \ll 1$. Thus, when $u_0 \approx u_m$, the recycled energy by the supercapacitor reaches the maximum in one switching period. Therefore, the system energy-regeneration efficiency is highly dependent on the supercapacitor initial terminal voltage and the DC-DC converter characteristics (including inductance, switching frequency, and capacitance).

3. Simulation Analysis

To analyze the effect of the supercapacitor initial terminal voltage on the suspension dynamics and energy-regeneration, a hybrid semiactive control strategy was applied to the vehicle single wheel model. Differential equations of the system dynamics are given as

$$\begin{aligned}m_2 \ddot{z}_2 + k(z_2 - z_1) + c_0(\dot{z}_2 - \dot{z}_1) - F_M &= 0, \\ m_1 \ddot{z}_1 + k(z_1 - z_2) + k_t(z_1 - q) + c_0(\dot{z}_1 - \dot{z}_2) + F_M &= 0, \\ \dot{q}(t) &= -0.111 \left[v_0 q(t) + 40 \sqrt{G_q(n_0)} v_0 w(t) \right].\end{aligned}\quad (13)$$

In the above equation, m_2 is the sprung mass, m_1 is the unsprung mass, $q(t)$ is the road displacement input, k is the spring stiffness, k_t is the tire stiffness, c_0 is the damping coefficient of the traditional damper, F_M is the electromagnetic damping force of the linear motor, $G_q(n_0)$ is the road roughness coefficient, $w(t)$ is white Gaussian noise with an average of zero, and v_0 is the vehicle speed.

The simulation situations were a speed of 30/s on the B level and the C level roads. Simulation parameters are listed in Table 1 [20].

In the simulation, the supercapacitor pack was composed by 12 supercapacitors (100 F, 2.5 V). Switching frequency was

FIGURE 2: The relationship between recycled energy by the supercapacitor and the initial terminal voltage.

20 KHz and duty ratio was 50%. Simulation results are shown in Figures 2–5.

According to Figure 2, recycled energy by the supercapacitor increased rapidly at first and then decreased slowly as the supercapacitor initial terminal voltage increased, while the suspension dynamic performance had no obvious change according to Figures 3–5. Therefore the effect of supercapacitor initial terminal voltage on suspension dynamics could be neglected.

4. Research into the Mode-Switching Control Strategy of Supercapacitor

A mode-switching control strategy of supercapacitor for the regenerative and semiactive suspension system was proposed based on the above simulation results. The control strategy can increase the energy-regeneration efficiency of the suspension system without influencing the suspension dynamics. Switching logic is shown in Figure 6.

When the supercapacitor terminal voltage is greater than the upper threshold, the charging capacitor turns into discharging mode and charges the vehicle battery, and when the supercapacitor terminal voltage is less than the lower threshold, the discharging capacitor turns into charging mode and recycles the electromotor vibration energy.

According to the above analysis, the effect of the supercapacitor terminal voltage on suspension dynamics can be neglected but has a great influence on energy-regeneration. For the simulation of B level road, the supercapacitor mode-switching range was [10 V, 20 V], while for the simulation of C level road, the mode-switching range was [15 V, 30 V].

After utilizing the mode-switching control strategy of the supercapacitor, simulation results of the system recycled energy W , the root-mean-square value of vehicle body acceleration a_w , the root-mean-square value of suspension dynamic travel SWS_{rms} , and the root-mean-square value of tire dynamic load DTL_{rms} are shown in Table 2. (1) denotes the mean value of the parameter, and (2) denotes the increased percentage of the parameter after utilizing the mode-switching strategy.

As is shown in Table 2, the vehicle body acceleration and the tire dynamic load both had improvement, which were

FIGURE 3: The relationship between vehicle body acceleration and supercapacitor initial terminal voltage.

FIGURE 4: The relationship between suspension dynamic travel and supercapacitor initial terminal voltage.

FIGURE 5: The relationship between tire dynamic load and supercapacitor initial terminal voltage.

not very obvious. The suspension dynamic travel got a little worse, which could be neglected. However, recycled energy by the supercapacitor greatly increased. Particularly in the simulation of C level road with a speed of 30 m/s, recycled energy had an increase by 17.8%. Thus, the mode-switching control strategy has no effect on the dynamic performance of vehicle body while bringing an apparent optimization to the energy-regeneration efficiency of the regenerative and semiactive suspension system.

5. Experiment Research

The output terminal of the linear motor was connected by a rectifier to the DC Boost converter, which was used to build

TABLE 2: Simulation results with mode-switching of the supercapacitor.

		W/J	$a_w/\text{m}\cdot\text{s}^{-2}$	$\text{SWS}_{\text{rms}}/\text{mm}$	$\text{DTL}_{\text{rms}}/\text{N}$
B-30	(1)	28.24	1.2304	8.495	654.3
	(2)	14%	-0.02%	0.1%	-0.005%
C-30	(1)	112.1	2.4608	16.994	1308.6
	(2)	17.8%	0	0.04%	-0.003%

the regenerative and semiactive suspension system. Then the whole equipment was installed to the hydraulic servo and vibration actuator platform with single channel to conduct

FIGURE 6: The switching logic of supercapacitor operation mode.

(a) Structure diagram of the suspension system

(b) Schematic diagram of the supercapacitor mode-switching

FIGURE 7: Experiment schematic diagram.

bench test. Finally, the experiment was conducted. Structure diagram of the suspension system is shown in Figure 7(a). The supercapacitor pack consisted of 12 capacitors (2.5 V 100 F) in series. The switching signal was frequency 20 KHz, duty ratio 50%, low level voltage 0 V, and high level voltage 5 V. The inductance was 3.7 mH. As is shown in Figure 7(b), control unit of the mode-switching control strategy was dSPACE, into which the control strategy was loaded based on Matlab and ControlDesk together. Then, dSPACE output PWM wave to control the supercapacitor mode-switching circuit.

The effect of supercapacitor terminal voltage on dynamics and energy-regeneration of the regenerative and semiactive suspension was analyzed with increasing the initial terminal

voltage gradually. Experimental situations were 30 m/s on B level and C level roads. Experimental results are shown in Figures 8–11.

According to Figure 8, recycled energy by the supercapacitor increased at first and then decreased as the supercapacitor initial terminal voltage increased. In the experimental situation of 30 m/s on B level road, recycled energy was much less than that in C level road situation, because output terminal voltage of the linear motor was much lower, making it very difficult for the supercapacitor to recycle energy.

According to Figures 9–11, the root-mean-square values of vehicle body acceleration, suspension dynamic travel, and tire dynamic load fluctuated randomly as the supercapacitor

FIGURE 8: The relationship between recycled energy by the supercapacitor and the initial terminal voltage.

FIGURE 9: The relationship between vehicle body acceleration and supercapacitor initial terminal voltage.

FIGURE 10: The relationship between suspension dynamic travel and supercapacitor initial terminal voltage.

FIGURE 11: The relationship between tire dynamic load and supercapacitor initial terminal voltage.

TABLE 3: Experiment results with mode-switching of the supercapacitor.

		W/J	$a_w/m \cdot s^{-2}$	SWS_{rms}/mm	DTL_{rms}/N
B-30	(1)	5.79	1.515	2.639	578.0
	(2)	35.9%	-0.26%	0.19%	-0.22%
C-30	(1)	53.60	2.751	5.166	1560.9
	(2)	24.9%	0.11%	-1.86%	0.1%

initial terminal voltage increased, but the fluctuations were small and showed no apparent rule. Instabilities of the test bench structure and sensors operation, as well as serious shakes and frictions of the displacement sensor expansion link, were major reasons of the fluctuations. The fluctuations on C level road were much larger than that on B level road, but the fluctuations on C level road were still relatively small.

The mode-switching circuit of the supercapacitor was applied to the regenerative and semiactive suspension system, and the influence mechanism of the supercapacitor mode-switching control strategy on system dynamics and regeneration performance was studied with experiments. As is shown in Figure 7(b), the control unit dSPACE output two opposite pulse signals (I and II) to two driver chips (IR2101), respectively. Then both driver chips output two opposite pulse signals to control the four switching tubes (①–④) and finally mode-switching of the supercapacitor was realized.

When the maximum and the minimum of the mode-switching voltage range were much closer to the corresponding supercapacitor terminal voltage at which recycled energy reached the maximum, the actually recycled energy would become larger. As for the actual circuit, frequent mode-switching of the supercapacitor will cause energy consumption of the circuit, which decreases the energy-regeneration efficiency. With comprehensive consideration, the mode-switching ranges of the supercapacitor on B level road and C level road are [3 V, 8 V] and [11 V, 23 V], respectively. Experimental results are shown in Table 3. (1) denotes the mean value of the parameter, and (2) denotes the increased percentage of the parameter after utilizing the mode-switching strategy.

The experimental result with mode-switching control strategy of the supercapacitor was in accordance with the simulation result. Fluctuation amplitude of dynamic performance increased in experiment compared with that in simulation, but the increment is less than 2%. And increment of energy-regeneration efficiency in experiment was always greater than that in simulation. Therefore, the effect of supercapacitor mode-switching control strategy on system dynamics can be neglected but greatly increases energy-regeneration efficiency of the system, which is highly valuable to practical engineering.

6. Conclusions

(1) As initial terminal voltage of the supercapacitor increases, vehicle body acceleration, suspension dynamic travel, and tire dynamic load have no obvious change while recycled

energy by the supercapacitor increases at first and then decreases.

(2) The proposed supercapacitor mode-switching control strategy for the regenerative and semiactive suspension system hardly influences the system dynamic performance but can greatly increase energy-regeneration efficiency of the system.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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