VIBRATION ENERGY RECOVERY SYSTEM OF VEHICLE SUSPENSION BASED ON ULTRASONIC SENSOR

by

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The current design of vibration energy recovery system for vehicle suspension does not analyze the vibration of the vehicle under different road conditions, resulting in the system's low energy recovery ratio, low recovery efficiency, and low energy utilization. Therefore, in this paper, the vibration energy recovery system of vehicle suspension based on ultrasonic sensors is proposed. The ultrasonic sensor is used to obtain the vibration information of the vehicle, and the vibration of the vehicle on the smooth and uneven roads is analyzed according to the obtained information. According to the analysis results, the design of the vibration energy recovery system for vehicle suspension is completed through four parts: the IGBT module, the control system, the direct thrust controller, and the energy management controller. The experimental results show that the system designed by the proposed method has a large energy recovery ratio, high recovery efficiency and high energy utilization rate.

Key words: *ultrasonic sensor, vehicle suspension, vibration energy, energy recovery, system design*

Introduction

The function of active suspension is simply to reduce vibration and active vibration reduction. Therefore, the research on active suspension mainly focuses on active vibration reduction [1]. Traditional vehicle suspension systems include elastic elements and damping elements. The damping element converts vibration energy into heat energy in the form of viscous friction, and finally dissipates this part of heat energy into the atmosphere [2]. If this energy can be recycled, the energy consumption of the car can be reduced, so as to achieve the purpose of saving energy [3].

Gao *et al*. [4] proposed an online control system for suspension vibration energy recovery for new energy vehicles. This method was based on the damping adjustment circuit of a high frequency DC-DC converter. By adjusting the duty cycle of the pulse width modulation signal driving the power field effect transistor, the output voltage could be adjusted based on the input voltage. Then the target electromagnetic torque was calculated during the damper working process, the armature current required to reach the reference torque was calculated, the actual current was sent to the PI controller for PI closed-loop adjustment, and the duty ratio of the driving PWM signal was output. Finally, the PWM controller drive the DC-DC converter with a 1 kHz adjustment frequency to achieve target torque following and energy recovery. This method did not obtain vehicle vibration information, and there was a problem of low energy

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recovery ratio. Chen *et al*. [5] proposed an energy recovery system of suspension vibration based on variable voltage charging. The system established a 4-DoF dynamic model and a variable voltage charging control linear motor model of 1/2 vehicle. The LQG control strategy was used to solve the ideal energy-feeding damping force. The theoretical model of the linear motor connected with the rectifier bridge was equivalent to a single-phase motor model, and the back-EMF, electromagnetic thrust coefficient, resistance and inductance parameters of the motor single-phase equivalent model were calculated. The charging voltage was used to solve the controller. The relative speed of the suspension and the ideal energy-feeding damping force were used as input to solve the actual charging voltage, and then realize the recovery of vibration energy. However, the system did not analyze the vibration of the vehicle under stable road conditions, resulting in the low energy recovery efficiency of the designed system. Kou *et al*. [6] proposed a vibration energy recovery system of electromagnetic compound energy-feeding suspension, which established a 2-DoF vehicle suspension model including an electromagnetic compound actuator, and proposed a semi-active control strategy composed of a main ring and an inner ring. The main loop obtained the ideal semi-active power through the linear quadratic Gaussian control strategy, and used the ant colony optimization algorithm to determine its control parameters to realize the recovery of vibration energy. However, the system did not obtain the vehicle's vibration information under unstable road conditions, and there was a problem of low energy utilization.

In order to solve the problems of the aforementioned systems, a vibration energy recovery system of vehicle suspension based on ultrasonic sensors is proposed and designed.

Vehicle vibration analysis

During the driving process of the vehicle, the road surface unevenness in the steady-state and the instantaneous excitation of the road surface in the sudden state will cause the vibration of the car [7], so the data obtained by the ultrasonic sensor is used to analyze the vibration condition of the vehicle when driving on these two types of roads.

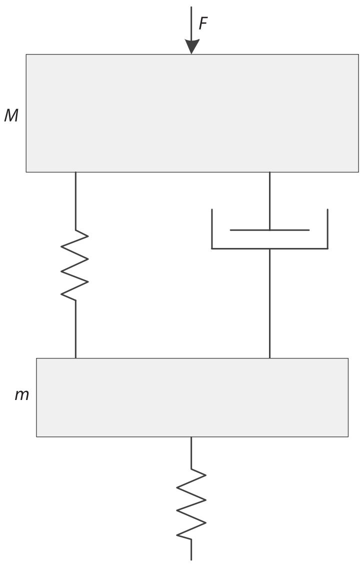

Figure 1. Quarter model

Vehicle vibration analysis on smooth roads

Road unevenness is a smooth and random process, and the frequency of road excitation is different under different grades of roads and different driving speeds. According to the focus of the research problem, only the vehicle body vibration caused by the road surface excitation is considered. Several mass-elastic elements or several rigid body systems are used to represent a vehicle model. The simplest multi-DoF discrete model has *Quarter car model* and *2-D vertical and pitch model* [8, 9]. These models can be used to analyze the most basic frequency and mode characteristics of the vehicle. Assuming that the mass distribution of the whole car is symmetrical, the structure of the vehicle is also symmetrical, the road surface stimulates the left and right wheels of the vehicle the same, the up and down movement of the front and rear wheels are independent of each other, so that one quarter of the car can be used to describe the verticality of the direction of movement. The *Quarter model* is shown in fig. 1.

The expression of the dynamic equation of the quarter car model:

$$M\dot{z} + C\dot{z} + K_s z = K_s z_u + C\dot{z}_u + F \tag{1}$$

$$m\ddot{z}_u + C\dot{z}_u + (K_s + K_l)z_u = K_s + C\dot{z} + K_l z_r \tag{2}$$

where m is the mass of the wheels and axles, K_l – the tire stiffness, M – the body mass, K_s – the spring stiffness of the suspension system, C – the damping of the suspension system's shock absorber, F – the vehicle's own excitation force, and z, z_u, z_r are the displacements of the body, axle, and road, respectively.

The stiffness K_s of the suspension system is generally much smaller than the stiffness K_l of the tires, and the body mass M is generally much larger than the wheel and axle mass m [10]. Therefore, for the vehicle body, its vibration frequency ω_s can be expressed:

$$\omega_s = \sqrt{\frac{K_s K_l}{(K_s + K_l)M}} \approx \sqrt{\frac{K_s}{M}} \tag{3}$$

This vibration frequency is very low, generally 1.1-2 Hz. This low frequency vibration mode can be approximated as the mode of the body mass and suspension spring system. For low frequency vibration, the vibration amplitude of tires and axles is not large, and the impact on vehicle body vibration is very limited [11].

Converting eqs. (1) and (2) into the frequency domain, the transfer function of the vehicle body to the road surface excitation force can be obtained, which is expressed:

$$\frac{Z}{Z_r} = \frac{K_r(K_s + jC\omega)}{(K_s + K_l m\omega^2 + jC\omega)(K_s - M\omega^2 + jC\omega) - (K_s + jC\omega)^2} \tag{4}$$

It reflects the output of vehicle body vibration obtained through the suspension system when the input is stimulated by the displacement of the road surface.

The auxiliary kinetic energy calculation equation:

$$E = \frac{mgK_l(K_s + jC\omega)}{(K_s + K_l - m\omega^2 + jC\omega)(K_s - M\omega^2 + jC\omega) - (K_s + jC\omega)^2} \tag{5}$$

In the quarter model, only the vertical vibration of the vehicle is considered, but in actual driving, there is not only vertical vibration, because the vertical movement of the front and rear axles is not synchronized, it will form relative rotation [12, 13], in this way, a new model is introduced. This model simplifies the car body into a rigid beam, considering both vertical and pitching vibrations. Therefore, this model is called *2-D vertical and pitching model*. The dynamic equation:

$$M\dot{z} = -k_f(z + l_1\theta) - k_r(z + l_2\theta) \tag{6}$$

$$I_y\ddot{\theta} = -k_f(z + l_1\theta)l_1 + k_r(z + l_2\theta)l_2 \tag{7}$$

where z is the vertical vibration displacement, θ – the pitch vibration angle, M – the body mass, I_y – the moment of inertia around the center of gravity, k_f, k_r are the stiffness of the suspension system of the front and rear wheel, respectively, and l_1, l_2 – the distances from the front and rear wheels to the center of gravity of the vehicle body.

Converting eqs. (6) and (7) into the frequency domain, the frequency of the model can be obtained, which is expressed:

$$\omega_n^2 = \frac{A_1 + A_3}{2} \mp \sqrt{\frac{(A_1 - A_3)^2}{4} + \frac{A_2^2}{r_y^2}} \tag{8}$$

In the equation, A_1, A_2, and A_3 are intermediate parameters, respectively:

$$A_1 = \frac{k_f + k_r}{M} \tag{9}$$

$$A_2 = \frac{k_f l_1 - k_r l_2}{M} \tag{10}$$

$$A_3 = \frac{k_f l_1^2 + k_r l_2^2}{M} \tag{11}$$

$$r_y^2 = \sqrt{\frac{I_y}{M}} \tag{12}$$

The two modes corresponding to the two frequencies in the equation are: the mode in which the vehicle body moves up and down around the center of beating, the vehicle body moves vertically in this mode and the mode in which the vehicle body rotates around the center of rotation, and the vehicle body does a pitching motion in this mode [14].

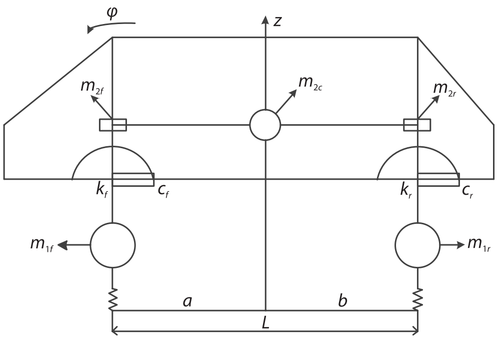

Figure 2. Plane model with 4-DoF

Vehicle vibration analysis under sudden conditions

The instantaneous excitation of the road surface in a sudden state is mainly generated by the speed bumps and pits on the random road surface. It depends on the parameters such as the shape and height of the speed bumps and pits to determine [15, 16]. When it passes through the speed bump from contact, there will be a huge change in acceleration in the vertical direction.

When the vehicle passes the speed bump, the vehicle body has only vertical vibration $Z(m)$ and pitch vibration φ. The front and rear axle masses m_{1f} and m_{1r} [kg] and have 2-DoF. The vehicle can be simplified into a plane model with 4-DoF, as shown in fig. 2.

Because the damping of the tire is much smaller than the damping of the damper in the suspension system, and the stiffness of the tire is much smaller than the stiffness of the elastic components in the suspension system, the stiffness and damping of the tire can be ignored [17], to further simplify the model. The body mass, m, and the moment of inertia, I, around the Y-axis are decomposed into three concentrated masses on the front axle, the rear axle and the center of mass according to the dynamic equivalent conditions. These three masses are connected by massless rigid rods. The size of is determined by three conditions:

– The total amount remains unchanged

$$m_{2f} + m_{2r} + m_{2c} = m \tag{13}$$

where m_{2f} is the mass of the front half of the vehicle body, m_{2r} – the mass of the rear half of the vehicle body, m_{2c} – the mass of the middle vehicle body, and m – the total mass of the vehicle body.

– The position of the center of mass remains unchanged

$$m_{2f}a - m_{2r}b = 0 \tag{14}$$

where a and b are the distance from the center of mass of the body mass to the front and rear axles.

– The value of the moment of inertia remains unchanged

$$I_y = m\rho_y^2 = m_{2f}a^2 + m_{2r}b^2 \tag{15}$$

where ρ_y is the radius of gyration around the horizontal y-axis.

According to the aforementioned three equations, three concentrated qualities can be obtained:

$$\begin{aligned} m_{2f} &= \frac{m\rho_y^2}{aL} \\ m_{2r} &= \frac{m\rho_y^2}{bL} \\ m_{2c} &= m\left(1-\frac{\rho_y^2}{ab}\right) \end{aligned} \tag{16}$$

where $L = a + b$ is the wheelbase of the vehicle, $\varepsilon = \rho_y^2/ab$, which is called the distribution coefficient of suspension mass, which determines the mass distribution of the front and rear axles of the vehicle. When $s = 1$, the mass $m_{2c} = 0$. When the vehicle is driving on the road, if the front wheels encounter uneven road surface and cause vibration, the mass m_{2f} will move, but the mass m_{2r} will not move, vice versa. After obtaining the vibration of the front and rear wheels, the body part between the two wheels can be calculated by linear interpolation obtain the corresponding movement [18, 19].

For vehicles traveling on the road, according to statistics, the suspension mass distribution coefficient of most vehicles is $\varepsilon = 0.8 \sim 1.2$, which is close to 1. The vibration model of the vehicle can be simplified as a model of two single-mass systems composed of the front wheel axle and the mass m_{2f} on the front wheel and the rear wheel axle and the mass m_{2r} on the rear wheel axle.

After simplifying the vehicle to a model of two single-mass systems, the vibration force equation is established for the situation when the vehicle passes through the speed bump. The simplified diagram of the vehicle passing the speed bump is shown in fig. 3.

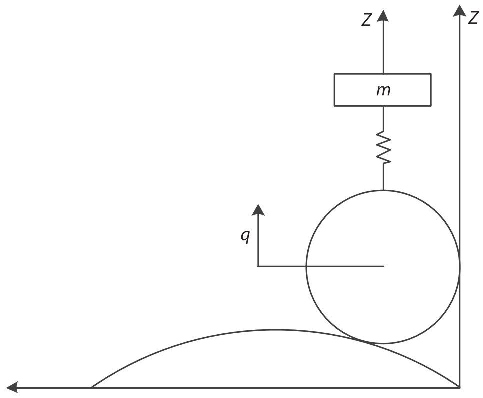

Figure 3. Schematic diagram of the car passing the speed bump

According to the co-ordinate system established in the figure, the force analysis of the vehicle body mass m [kg] is carried out. The z is the displacement co-ordinate of the mass block. Since both ends of the vehicle spring are moving, the deformation of the vehicle spring at any instant is $z - q$. The c is the elastic coefficient of the spring, and the elastic restoring force is $c(z - q)$. According to Newton's law, the following vibration differential equation can be established:

$$m\ddot{z} + cz - cq = 0 \tag{17}$$

The previous equation is the vibration equation of the vehicle passing through the speed bump, and q is the input function of the ground.

When the vehicle passes the speed bump at speed v, then:

$$q = A\sin\omega t \tag{18}$$

In this case, there is:

$$m\ddot{z} + cz = cA\sin\omega t \tag{19}$$

$c/m = k^2$, $cA/m = h$, and the aforementioned equation is changed to:

$$\frac{\mathrm{d}^2 z}{\mathrm{d}^2 l^2} + k^2 z = h\sin\omega t \tag{20}$$

The previous equation is the initial value problem of the second-order non-homogeneous linear differential equation with constant coefficients. When the vehicle is driving on the road, the unevenness of the road will also cause the vehicle to vibrate, but the unevenness of the road is much smaller than the height of the speed bump, so the impact of the unevenness of the road is not considered, that is, before the vehicle is passing the speed bump ($t < 0$) is in a stable state [20]. So, the time $t = 0$ is the time when the vehicle starts to pass the speed bump, there are: $z(0) = 0$, $z'(0) = 0$.

Therefore, the movement law of the up and down vibration of the vehicle body is:

$$z = -\frac{h\omega}{(k^2 - \omega^2)k}\sin kt + \frac{h}{k^2 - \omega^2}\sin\omega t \tag{21}$$

It reflects the output of vehicle body vibration obtained through the suspension system when the road surface is suddenly ex-cited and input.

The auxiliary kinetic energy at this time is:

$$E = m\mathrm{g}\left[\frac{h}{k^2 - \omega^2}\sin\omega t - \frac{h\omega}{(k^2 - \omega^2)k}\sin kt\right] \tag{22}$$

Vibration energy recovery system of vehicle suspension

The vibration energy recovery system of vehicle suspension mainly considers two functions, one is active vibration reduction, which is smoothness, and the other is energy saving, which is energy recovery. Taking into account the functions of the aforementioned two aspects, the vibration energy recovery system of vehicle suspension is designed, which mainly includes: quarter suspension, control system, energy management circuit, IGBT*, etc.* Under the co-ordinated action of the aforementioned parts, the vibration energy recovery system of vehicle suspension can realize the functions of active vibration reduction and energy recovery. The structural block diagram of the vibration energy recovery system of vehicle suspension is shown in fig. 4.

– The IGBT module

Since the electromagnetic actuator used is a three-phase AC type, and the vehicle power supply is usually a DC type, when the electromagnetic actuator works as a motor, it is necessary to invert the DC power into AC power to supply power to the electromagnetic actuator, that is, to achieve DC-AC conversion; When the electromagnetic actuator works for the generator, the AC power needs to be rectified into DC power to charge the power source, that is, AC-DC conversion is realized. Judging from the type of DC power supply, it can be divided into voltage source type and current source type. From the perspective of circuit structure, it can be divided into single-phase half-bridge, single-phase full-bridge, and three-phase bridge.

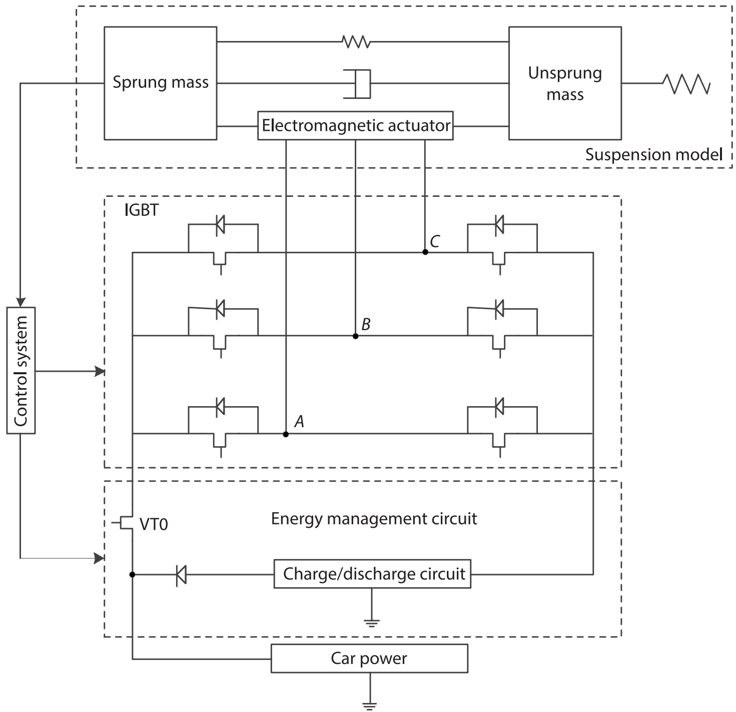

Figure 4. Structural block diagram of vibration energy recovery system of vehicle suspension

Since the linear motor used in the proposed method is a three-phase AC type, the proposed method uses a three-phase bridge voltage inverter/rectifier module, that is, an IGBT module.

The IGBT insulated gate bipolar transistor is a composite fully-controlled voltage-driven power semiconductor device composed of BJT and MOSFET, which has the advantages of both the high input impedance of MOSFET and the low on-voltage drop of GTR [21]. The saturation voltage of the GTR is reduced, the current-carrying density is large, but the drive current is large. The MOSFET drive power is small, the switching speed is fast, but the conduction voltage drop is large, and the current-carrying density is small. The IGBT combines the advantages of the previously described two devices, with low driving power and reduced saturation voltage. It is very suitable to be used in converter systems with a DC voltage of 600 V and above, such as AC motors, frequency converters, switching power supplies, lighting circuits, traction drives and other fields.

In the frequency conversion speed regulation system of the AC motor, the inverter is an important component, and the control of the motor is mainly realized through the control of the inverter. Shown in fig. 5 is a voltage-type inverter circuit.

– Control system

According to the performance requirements of the suspension system and the characteristics of the linear motor actuator, the control system of the active suspension is designed. The control system is mainly composed of three controllers, which are LQR controller, electromagnetic force controller, and energy management controller. The three controllers constitute the active damping control and energy recovery control of the entire suspension, which constitute the so-called ECU. The functions of the three controllers are:

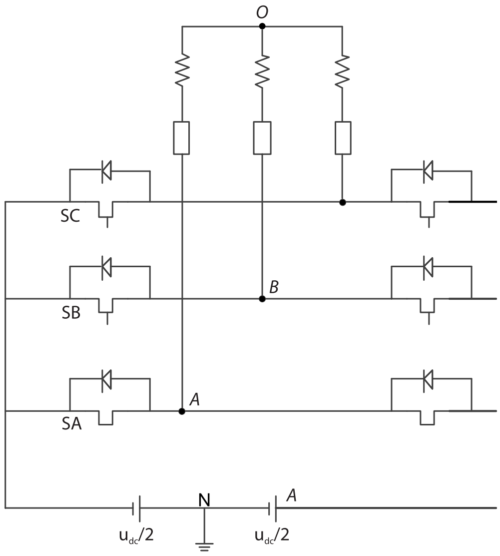

Figure 5. Schematic diagram of IGBT

– *Energy management controller*: the energy management controller mainly controls the flow of energy by judging the working condition of the electromagnetic actuator.

– *Optimal controller*: according to the vehicle body vibration signal detected by the sensor, the optimal control force of the suspension under the vibration condition and the speed of suspension vibration are calculated.

– *Electromagnetic force controller*: the electromagnetic force controller adopts the direct thrust control method. According to the optimal control force and the vibration speed of the suspension, the electromagnetic force controller generates the control signal of the IGBT to output the corresponding three-phase voltage [22].

– Direct thrust controller

In the driving process of the vehicle, the active vibration reduction of the vehicle is actually achieved through the control of the electromagnetic force of the linear asynchronous motor, so the rapid, accurate and reliable control of the electromagnetic force of the actuator is the key to suspension research [23].

The electromagnetic actuator is controlled by the direct thrust control method. Direct thrust control is actually direct torque control, because the relative motion of the primary and secondary motor of the linear motor is not a rotary motion but a linear motion. At this time, the electromagnetic torque is the electromagnetic thrust, and the two can be interchanged, as shown in eq. (23), so here the direct torque control is called direct thrust control.

$$T_e = F_e d = F_e \frac{p\tau}{\pi} \tag{23}$$

where p is the number of poles and τ – the pole pitch.

– Design of energy management controller

Generally speaking, the function of the energy management controller is to manage and control the energy of the suspension. Specifically, it includes two aspects: first, according to the working mode of the electromagnetic actuator, control the flow of energy and second, when the actuator is in generator mode, it controls the charging process [24]. The energy management circuit of suspension includes driving circuit and energy storage recovery circuit.

- Charge/discharge circuit

When the electromagnetic actuator works as a generator, the mechanical energy is converted into alternating current, which is rectified by the inverter to become direct current and then sent to the charging/discharging circuit. The charge/discharge circuit plays the role of transferring and temporarily storing electrical energy in the energy recovery system of the entire smart suspension.

- Vehicle power supply

At present, the vehicle power supply is usually a battery. The battery, as an energy storage unit, plays different roles in different stages of system operation. When the electromagnetic actuator is operating as a motor, it provides energy to the main circuit. When the electromagnetic actuator is operating as a generator, the generated electric energy charges the battery through the main circuit [25].

The internal resistance of the battery changes during charging and discharging. When the battery is discharged, the internal resistance is assumed to be R_d, when the battery is charged, the internal resistance is assumed to be R_c, and the battery current i_b (when the battery is discharged, i_b takes the positive direction):

$$i_b = \begin{cases} \dfrac{E_b - u_{dc}}{R_d} & \text{when the battery is discharged, } u_{dc} < E_b \\ -\dfrac{u_{dc} - E_b}{R_d} & \text{while charging the battery, } u_{dc} \geq E_b \end{cases} \tag{24}$$

- Energy management controller

The energy management controller is mainly composed of the following parts: vehicle power supply, IGBT inverter, charge/discharge circuit, electromagnetic actuator mode switch VT0, and one-way diode VD0. The function of VT0 is: when the electromagnetic actuator is in the motor mode, it needs to consume the electric energy of the on-board power supply, the VT0 switch is turned on, and the electric energy flows from the on-board power supply to the electromagnetic actuator through VT0. When the electromagnetic actuator is in the generator mode, VT0 is turned off. The role of the unidirectional diode VD0 is to ensure the unidirectional flow of current, that is, when the electromagnetic actuator is in the generator mode, the generated electric energy enters the energy storage charging circuit through VD0, thereby charging the power source.

The energy management controller uses the positive or negative of the product of the suspension speed and the electromagnetic force to perform the pattern recognition of the linear motor electromagnetic actuator. The specific process is:

– When $F_e(\dot{z}_1 - \dot{z}_2) > 0$, the electromagnetic actuator is in motor mode, the on-board power supply outputs electrical energy to the linear motor electromagnetic actuator, and the electromagnetic actuator generates electromagnetic force to suppress vehicle vibration.
– When $F_{ij}(\dot{z}_{1ij} - \dot{z}_{2ij}) < 0$, the electromagnetic actuator is in generator mode, and the electric energy generated by the linear motor electromagnetic actuator charges the on-board power supply through the energy storage circuit.

According to the aforementioned principles, the specific process and principle of energy control of the energy management controller are:

– When the electromagnetic actuator is running in the motor state, the suspension consumes the energy of the on-board power supply, so the on-board power supply supplies power to the electromagnetic actuator through VT0, that is, VT0 is turned on at this time;
– When the electromagnetic actuator is running in the generator state, VT0 is turned off at this time, and the electromagnetic actuator generates electrical energy. The generated electrical energy enters the charging/discharging circuit through VD0. At this time, the electrical energy is temporarily stored in capacitor A or B.
– When the capacitor B is charged to saturation, the controller controls the controllable switches A1 and B1 to turn on. At this time, capacitor A is the charging capacitor and capacitor B is the discharging capacitor.
– When the capacitor B is charged to saturation, the controller controls the controllable switch when the tubes A2 and B2 are turned on, the capacitor A is a discharging capacitor and the capacitor B is a charging capacitor. The electric energy from the charging/discharging circuit charges the on-board power supply.

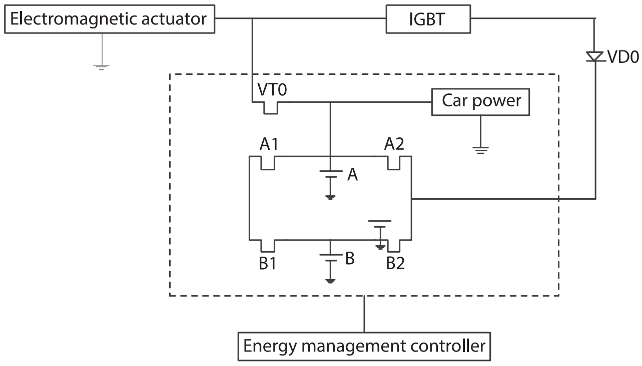

Figure 6. Schematic diagram of energy management control circuit

The energy management controller controls the on-off of the switch tube VT0 by judging the operating state of the electromagnetic actuator, so as to control the charging and discharging of the on-board power supply. At the same time, the switch tubes A1, B1, and A2, and B2 are switched on and off during charging, so as to realize the temporary storage of electric energy in the charging/discharging circuit, fig. 6.

Experiments and discussion

In order to verify the overall effectiveness of the vibration energy recovery system of vehicle suspension based on ultrasonic sensors, the vibration energy recovery system of vehicle suspension based on ultrasonic sensors is tested on the MATLAB platform. The vehicle suspension vibration energy recovery system based on ultrasonic sensors, System 1, the online control system of suspension vibration energy recovery for new energy vehicles, System 2, the energy recovery system of suspension vibration based on variable voltage charging, System 3, and the energy recovery system of electromagnetic composite energy-feeding suspension vibration, System 4, are adopted, respectively to perform vibration energy recovery test.

Analysis of the data in tabs. 1-4 shows that the energy recovered by System 1 is higher than the energy recovered by Systems 2-4, and the energy recovery ratio of System 1 is high.

Table 1. Energy recovery test results of System 1

Traffic	Motor energy consumption [J]	Vehicle vibration energy [J]	Total energy consumption [J]	Energy recovery [J]	Net energy consumption [J]	Energy recovery ratio
Road Condition 1	1468.1	2315.1	3783.2	561.2	3222	14.8%
Road Condition 2	1456.2	2546.5	4002.7	551.3	3451.4	13.7%
Road Condition 3	1442.5	2556.8	3999.3	549.8	3449.5	13.7%
Road Condition 4	1530.1	2812.1	4342.2	557.4	3784.8	12.8%
Road Condition 5	1521.3	2134.6	3655.9	591.4	3064.5	16.1%

Table 2. Energy recovery test results of System 2

Traffic	Motor energy consumption [J]	Vehicle vibration energy [J]	Total energy consumption [J]	Energy recovery [J]	Net energy consumption [J]	Energy recovery ratio
Road Condition 1	1468.1	2315.1	3783.2	352.1	3431.1	9.3%
Road Condition 2	1456.2	2546.5	4002.7	361.5	3641.2	9%
Road Condition 3	1442.5	2556.8	3999.3	334.8	3664.5	8.3%
Road Condition 4	1530.1	2812.1	4342.2	314.6	4027.6	7.2%
Road Condition 5	1521.3	2134.6	3655.9	322.7	3333.2	8.8%

Table 3. Energy recovery test results of System 3

Traffic	Motor energy consumption [J]	Vehicle vibration energy [J]	Total energy consumption [J]	Energy recovery [J]	Net energy consumption [J]	Energy recovery ratio
Road Condition 1	1468.1	2315.1	3783.2	401.3	3381.9	10.6%
Road Condition 2	1456.2	2546.5	4002.7	416.5	3586.2	11.6%
Road Condition 3	1442.5	2556.8	3999.3	394.7	3604.6	9.9%
Road Condition 4	1530.1	2812.1	4342.2	399.8	3942.4	9.2%
Road Condition 5	1521.3	2134.6	3655.9	387.4	3268.5	10.6%

Table 4. Energy recovery test results of System 4

Traffic	Motor energy consumption [J]	Vehicle vibration energy [J]	Total energy consumption [J]	Energy recovery [J]	Net energy consumption [J]	Energy recovery ratio
Road Condition 1	1468.1	2315.1	3783.2	361.5	3421.7	9.6%
Road Condition 2	1456.2	2546.5	4002.7	332.6	3670.1	8.3%
Road Condition 3	1442.5	2556.8	3999.3	387.8	3611.5	9.7%
Road Condition 4	1530.1	2812.1	4342.2	345.6	3996.6	8%
Road Condition 5	1521.3	2134.6	3655.9	358.9	3297	9.8%

According to fig. 7, the voltage of the capacitor is zero at time zero, and there is no energy stored in the capacitor. After that, with the increase of time, the capacitor voltage of System 1 increases continuously, indicating that the system has acquired the vehicle suspension at this time. The increase in the capacitance voltage of the System 2 is relatively low, and the Systems 3 and 4 both obtain the vibration energy of the vehicle suspension after a period of time.

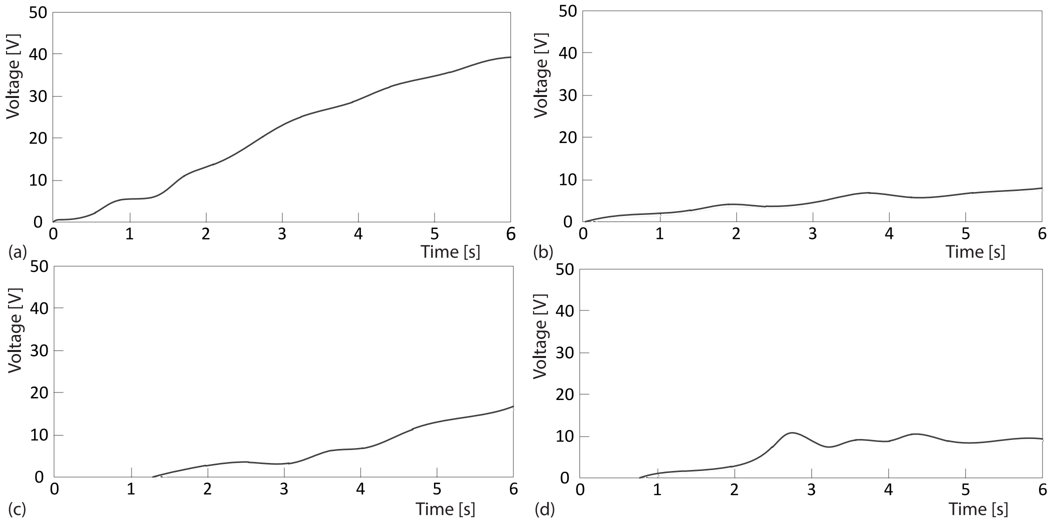

Figure 7. Capacitor voltage changes of the four systems; (a) capacitor voltage change of System 1, (b) capacitor voltage change of System 2, (c) capacitance voltage change of System 3, and (d) capacitor voltage change of System 4

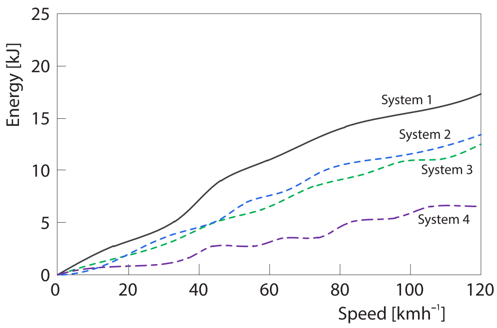

Figure 8. Actuator generates electricity

It can be seen from fig. 8 that with the acceleration of vehicle speed, the power generation of the actuators of Systems 1-4 continues to increase, but the power generation of the actuators of System 1 is much higher than that of Systems 2-4. The electric energy generated by the actuator indicates that the actuator has obtained more energy during operation. The higher the electric energy generated by the actuator is, the higher the utilization rate of the vibration energy of the vehicle suspension is, which verifies the effectiveness of the System 1.

In summary, the system designed by System 1 has a high energy recovery ratio, high recovery efficiency, and high energy utilization, because before the design of the vibration energy recovery system of vehicle suspension, according to the energy obtained by ultrasonic sensor, System 1 analyzes the vibration of vehicle suspension. According to the analysis results, a vibration energy recovery system of vehicle suspension is designed, which improves the recovery ratio, efficiency and utilization rate of energy.

Conclusions

Suspension is an important functional component in automobile structure, and its performance directly affects the overall performance of the vehicle's handling and ride comfort. At present, in the field of vehicle suspension research, whether it is a passive suspension or an active or semi-active suspension, its function is to attenuate the external excitation imposed on the vehicle to obtain good ride comfort. In the current international environment where energy-saving, emission-reduction and ecological vehicles are advocated, the research on suspensions that cannot only reduce vehicle vibration, but also recover vehicle vibration energy, appears to be of great significance. The current vibration energy recovery system of vehicle suspension has the problems of low energy recovery ratio, low recovery efficiency and low energy utilization. Thus, in this paper, a vibration energy recovery system of vehicle suspension based on ultrasonic sensors is proposed. Firstly, the vehicle vibration conditions on different roads are analyzed. According to the analysis results, a vibration energy recovery system of vehicle suspension is constructed, which improves the vehicle energy recovery ratio, recovery efficiency and energy utilization rate.

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