

# Study on coupled shock absorber system using four electromagnetic dampers

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**Abstract.** Recently, the electromagnetic damper, which is composed of an electric motor, a ball screw, and a nut, was proposed. The electromagnetic damper has high responsiveness, controllability, and energy saving performance. It has been reported that it improved ride comfort and drivability. In addition, the authors have proposed a coupling method of two electromagnetic dampers. The method enables the characteristics of bouncing and rolling or pitching motion of a vehicle to be tuned independently. In this study, the authors increase the number of coupling of electromagnetic dampers from two to four, and propose a method to couple four electromagnetic dampers. The proposed method enables the characteristics of bouncing, rolling and pitching motion of a vehicle to be tuned independently. Basic experiments using proposed circuit and motors and numerical simulations of an automobile equipped with the proposed coupling electromagnetic damper are carried out. The results indicate the proposed method is effective.

## 1. Introduction

Ride comfort and drivability of automobiles depends on suspension systems. In order to improve these performances, various methods for motion control with hydraulic shock absorbers have been developed, such as passive suspension with a non-linear damping force characteristic by structural contrivance and active suspension system [1] using actuator forces based on state quantity.

In recent years, with the aim of de-oiling, energy saving and high performance, active suspension systems using an electric motor have been proposed [2] [3]. And then, as a new component of next-generation suspension system, the authors proposed an electromagnetic damper [4] utilizing interconversion to kinetic energy and electric energy by electric motor. Electromagnetic damper is applicable to not only automobiles but also railways [5] and ships [6].

The electromagnetic damper has two remarkable characteristics. One is that the electromagnetic damper has various functions such as a passive damper, an actuator, an energy regenerator, a sensor, and a spring, depending on the electric circuit connected to its electric motor. By designing the electric circuit, the electromagnetic damper can realize non-linear damping characteristic which a practical oil damper has [7], and realize the energy saving active suspension by the function of an actuator and a generator [8].

The other is that coupling of multiple electromagnetic dampers can be constructed more easily than that of hydraulic dampers because electric motors can be connected with conductive wires, which can be installed in the vehicle more easily than hydraulic pipelines.

Utilizing these characteristics, the authors have already proposed a coupling methods of two electromagnetic dampers, which enables the damping characteristics of bouncing and rolling or



pitching motion of a vehicle to be tuned independently [9], and can realize anti-rolling suspension without a stabilizer mechanism [10].

In this paper, the authors propose a coupling method of four electromagnetic dampers which enables the damping characteristics of bouncing, rolling and pitching motion of a vehicle to be tuned independently.

## 2. Electromagnetic damper

### 2.1. Principle of electromagnetic damper

Figure 1 shows the basic concept of the electromagnetic damper for automobiles, which is a representative example of the electromagnetic devices. Its basic structure is shown in Figure 2. The electromagnetic damper is composed of an electric motor, a ball screw, and a nut. The stroke of the electromagnetic damper rotates the ball screw and the motor, and the electromagnetic force of the motor produced by the induced voltage generates the damping force in the direction of the damper stroke.



Figure1 Electromagnetic damper (2<sup>nd</sup> prototype)

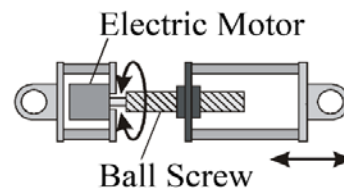


Figure2 Basic structure of electromagnetic damper

### 2.2. Model of electromagnetic damper

In this paper, the authors utilize a DC motor for the electromagnetic damper. The induced voltage  $e$  of the motor and the output force of the motor  $f$  is expressed as follows:

$$e = -G\dot{z}, \quad (1)$$

$$f = -Gi, \quad (2)$$

where  $z$  is stroke of the electromagnetic damper, and  $i$  is current of the motor.  $G$  is a specific constant of the electromagnetic damper, which is an equivalent of the torque constant of the motor converted from rotational to translational motion. When the motor is connected to a resistance  $R_{ex}$  as shown in Figure 3, the output force  $f$  is expressed as follows:

$$f = -\frac{G^2}{r + R_{ex}} \dot{z}, \quad (3)$$

where  $r$  is the internal resistance of the motor.

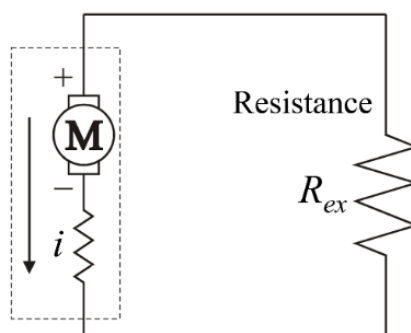


Figure3. A motor connected to a resistance

In addition to this, the electromagnetic damper generates inertia force [11], which originates in the inertia moment of the rotor of the motor, and friction forces at mechanical contact points. However, this study neglects these forces and assumes that electromagnetic dampers generate only electromagnetic force since these forces are not significant and negligible.

### 3. Coupling of electromagnetic dampers

#### 3.1. Uncoupled four electromagnetic damper

This paper discusses the performance of the proposed coupled damper on 3 DOF system; bounce, roll and pitch as shown in Figure 4.  $z_{fr}$ ,  $z_{fl}$ ,  $z_{rr}$ , and  $z_{rl}$  indicate the stroke of each electromagnetic damper,  $l_t$  and  $l_w$  indicate a half of the length of the tread and wheel-base of an automobile,  $z$  indicates the bounce displacement, and  $\phi$  and  $\theta$  indicate roll or pitch angle, respectively.

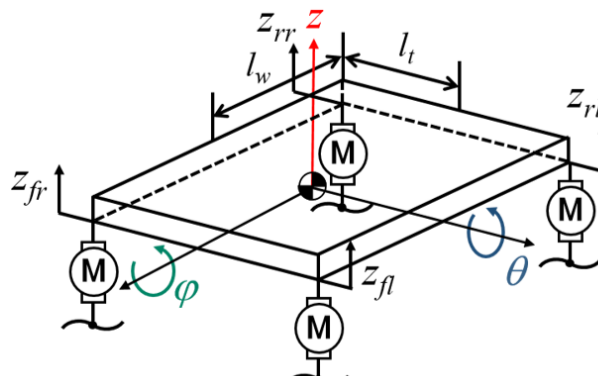


Figure4 3DOF model

Stroke of each dampers  $z_{fr}$ ,  $z_{fl}$ ,  $z_{rr}$ , and  $z_{rl}$  are expressed as follows:

$$z_{fr} = z - l_t \phi - l_w \theta, \quad (4)$$

$$z_{fl} = z + l_t \phi - l_w \theta, \quad (5)$$

$$z_{rr} = z - l_t \phi + l_w \theta, \quad (6)$$

$$z_{rl} = z + l_t \phi + l_w \theta. \quad (7)$$

According to Eqs. (4) - (7), output forces of each of four electromagnetic dampers are derived as shown in Eqs. (8) - (11).

$$F_{fr} = -\frac{G^2}{r + R_{fr}} (\dot{z} - l_t \dot{\phi} - l_w \dot{\theta}), \quad (8)$$

$$F_{fl} = -\frac{G^2}{r + R_{fl}} (\dot{z} + l_t \dot{\phi} - l_w \dot{\theta}), \quad (9)$$

$$F_{rr} = -\frac{G^2}{r + R_{rr}} (\dot{z} - l_t \dot{\phi} + l_w \dot{\theta}), \quad (10)$$

$$F_{rl} = -\frac{G^2}{r + R_{rl}} (\dot{z} + l_t \dot{\phi} + l_w \dot{\theta}). \quad (11)$$

Therefore, the bounce damping force  $F_b$ , roll damping moment  $M_r$ , and pitch damping moment  $M_p$  are derived as follows:

$$F_b = F_{fr} + F_{fl} + F_{rr} + F_{rl} = -c_a \dot{z} - c_b l_t \dot{\phi} - c_c l_w \dot{\theta}, \quad (12)$$

$$M_r = l_t \left\{ (F_{fl} + F_{rl}) - (F_{fr} + F_{rr}) \right\} = -c_b l_t \dot{z} - c_a l_t^2 \dot{\phi} - c_d l_t l_w \dot{\theta}, \quad (13)$$

$$M_p = l_w \left\{ (F_{rr} + F_{rl}) - (F_{fr} + F_{fl}) \right\} = -c_c l_w \dot{z} - c_d l_t l_w \dot{\phi} - c_a l_w^2 \dot{\theta}, \quad (14)$$

where  $c_a$ ,  $c_b$ ,  $c_c$  and  $c_d$  are constant values expressed by the following Eqs. (15)-(18):

$$c_a = G^2 \left( \frac{1}{r + R_{fr}} + \frac{1}{r + R_{fl}} + \frac{1}{r + R_{rr}} + \frac{1}{r + R_{rl}} \right), \quad (15)$$

$$c_b = G^2 \left( -\frac{1}{r + R_{fr}} + \frac{1}{r + R_{fl}} - \frac{1}{r + R_{rr}} + \frac{1}{r + R_{rl}} \right), \quad (16)$$

$$c_c = G^2 \left( -\frac{1}{r + R_{fr}} - \frac{1}{r + R_{fl}} + \frac{1}{r + R_{rr}} + \frac{1}{r + R_{rl}} \right), \quad (17)$$

$$c_d = G^2 \left( \frac{1}{r + R_{fr}} - \frac{1}{r + R_{fl}} - \frac{1}{r + R_{rr}} + \frac{1}{r + R_{rl}} \right). \quad (18)$$

If  $R_{fr}=R_{fl}=R_{rr}=R_{rl}=R_{ex}$ ,  $c_a=4G^2/(r+R_{ex})$ ,  $c_b=c_c=c_d=0$ . In this case, Eqs. (12) - (14) are derived as follows:

$$F_b = -4 \frac{G^2}{r + R_{ex}} \dot{z}, \quad (19)$$

$$M_r = -4 \frac{G^2 l_t^2}{r + R_{ex}} \dot{\phi}, \quad (20)$$

$$M_p = -4 \frac{G^2 l_w^2}{r + R_{ex}} \dot{\theta}. \quad (21)$$

These equations indicate that the resistance  $R_{ex}$  connected to each motor of electromagnetic dampers decides the damping characteristic of bouncing, rolling, and pitching motion simultaneously.

### 3.2. Independent tuning of damping characteristics for bouncing, rolling and pitching

In order to tune damping characteristics of bouncing, rolling and pitching motion independently, the authors propose a circuit as shown in Figure 5.

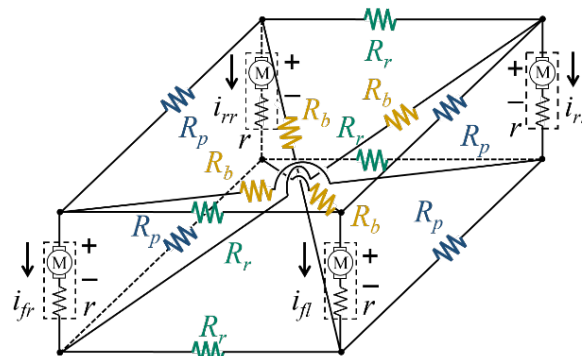


Figure5 Circuit of proposed system

In Figure5, The  $R_b$ ,  $R_r$ , and  $R_p$  indicate resistances to tune damping characteristics of bouncing, rolling and pitching motion, respectively. When four electromagnetic dampers are coupled by this circuit and induced voltages of each motor are  $-G\dot{z}_{fr}$ ,  $-G\dot{z}_{fl}$ ,  $-G\dot{z}_{rr}$ , and  $-G\dot{z}_{rl}$ , current of each motor  $i_{fr}$ ,  $i_{fl}$ ,  $i_{rr}$  and  $i_{rl}$  are expressed as follows by Kirchhoffs law:

$$i_{fr} = -\frac{G}{r + R_b} \dot{z} + \frac{Gl_t}{r + R_r} \dot{\phi} + \frac{Gl_w}{r + R_p} \dot{\theta} \quad (22)$$

$$i_{fl} = -\frac{G}{r + R_b} \dot{z} - \frac{Gl_t}{r + R_r} \dot{\phi} + \frac{Gl_w}{r + R_p} \dot{\theta} \quad (23)$$

$$i_{rr} = -\frac{G}{r + R_b} \dot{z} + \frac{Gl_t}{r + R_r} \dot{\phi} - \frac{Gl_w}{r + R_p} \dot{\theta} \quad (24)$$

$$i_{rl} = -\frac{G}{r + R_b} \dot{z} - \frac{Gl_t}{r + R_r} \dot{\phi} - \frac{Gl_w}{r + R_p} \dot{\theta} \quad (25)$$

From Eqs. (22) - (25), the bounce damping force  $F_b$ , roll damping moment  $M_r$ , and pitch damping moment  $M_p$  are expressed as follows:

$$F_b = -4 \frac{G^2}{r + R_b} \dot{z} \quad (26)$$

$$M_r = -4 \frac{G^2 l_t^2}{r + R_r} \dot{\phi} \quad (27)$$

$$M_p = -4 \frac{G^2 l_w^2}{r + R_p} \dot{\theta} \quad (28)$$

These equations indicate that  $R_b$ ,  $R_r$ , and  $R_p$  determine the damping characteristics with relation to bounce, roll and pitch independently.

## 4. Experiment

### 4.1. Experimental setup

As basic experiments of independent damping tuning of 3 DOF, torque characteristics measurement was carried out using four pairs of the motors and the proposed electric circuit. The experimental setup

is shown in Figure 6. The tested motors are loaded by the other electric motors, and the output torques of the motors are measured. The tested motors are DC motors whose rating output, torque constant and internal resistance are 150W, 60mN·m/A, and 1.3Ω.

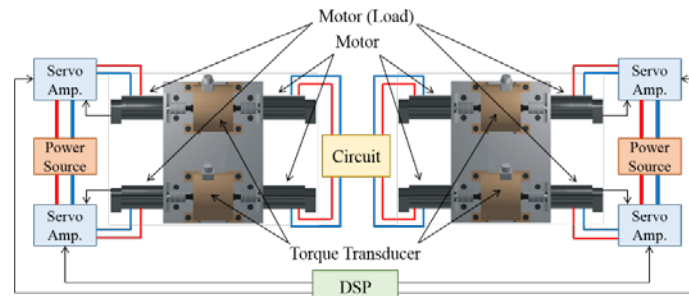


Figure 6 Experimental setup

#### 4.2. Independent damping tuning experiment

The damping torque of each motor was measured under the situation where four motors were coupled electrically by the proposed circuit, and the revolution speed of the each motor is controlled so that the body in Figure 4 makes bouncing, rolling, and pitching motion in the form of sine wave. The condition of resistances in proposed circuit is that resistance  $R_t$  and  $R_r$  are kept at 1.0Ω, and the resistance  $R_p$  is varied as 0(shorted), 0.47, 1.0, 2.0, and 4.7Ω.

The bounce, roll, and pitch damping torque characteristics against bounce, roll and pitch revolution speed of the motor are shown in Figure 7. The revolution speed is equivalent to suspension stroke speed.

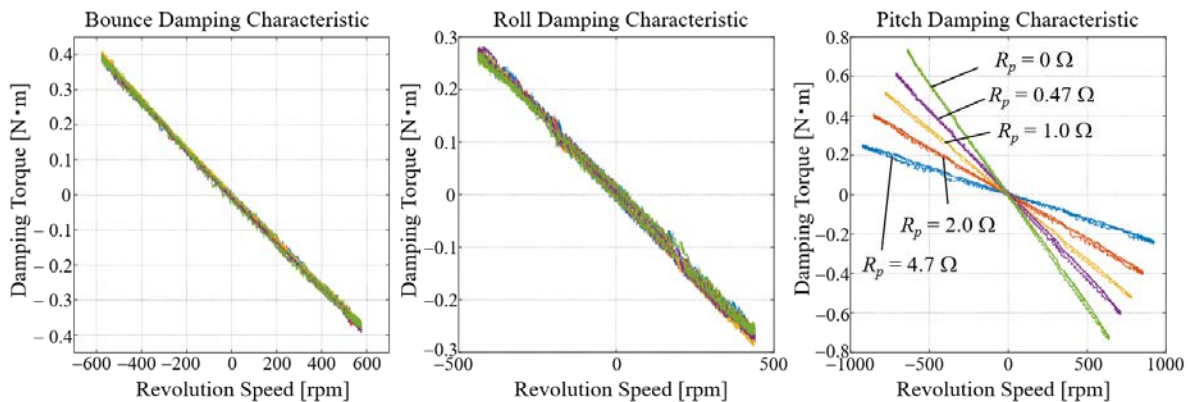


Figure 7 Damping torque characteristics

Figure 7 indicates that the change of resistance  $R_p$  varies only the pitch damping characteristic without any effect on bounce and roll damping characteristics. In a similar way, the other experimental results show that the resistance  $R_b$ , and  $R_r$  changes the damping characteristics of bouncing and rolling independently.

### 5. The dynamics of a vehicle with coupled electromagnetic dampers

#### 5.1. Full vehicle model and the specifications

A numerical simulations is executed using a full vehicle model considering bouncing, rolling and pitching motion as shown in Figure 8. The vehicle is assumed as a commonly used ordinary vehicle, and its specifications are shown in Table 1. The specifications of the electromagnetic damper is shown in Table 2. The electromagnetic dampers are installed in place of the normal oil dampers.

Table 1 Values of the parameters

Description	Symbol	Value
Unsprung mass	$m_1$	50[kg]
Sprung mass	$m_2$	1600[kg]
Roll moment of inertia	$I_{xx}$	1000[kg·m <sup>2</sup> ]
Pitch moment of inertia	$I_{yy}$	2400[kg·m <sup>2</sup> ]
Tire stiffness	$k_1$	240000[N/m]
Front spring stiffness	$k_{2f}$	18000[N/m]
Rear spring stiffness	$k_{2r}$	22500[N/m]
Distance between gravity center of sprung mass and front suspension	$l_f$	1.2[m]
Distance between gravity center of sprung mass and rear suspension	$l_r$	1.5[m]
Tread	$2l_t$	1.5[m]
Wheel base	$l_f + l_r$	2.7[m]

Table 2 Specifications of the electromagnetic damper

Description	Symbol	Unit	Value
Motor constant	$G$	N/A=V(m·sec)	124.96
Internal resistance	$r$	$\Omega$	1.16

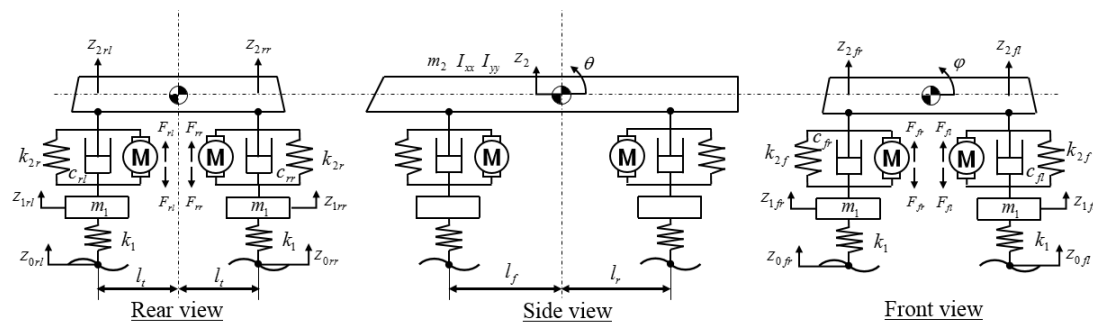
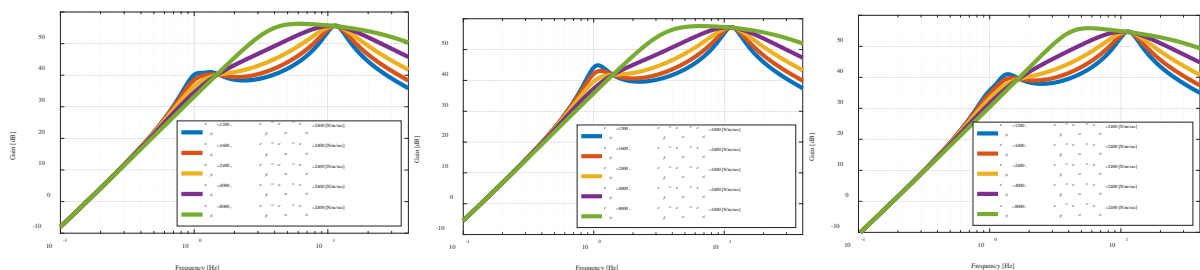


Fig.8 Full vehicle model

### 5.2. Frequency characteristics

Frequency responses of the full vehicle model are calculated in the case of normal (uncoupled) dampers. The condition of damping coefficients of each damper is that  $c_{fl}$ ,  $c_{rr}$  and  $c_{rl}$  are kept at 2400 N/m/s, and  $c_{fr}$  is varied as 1200, 1600, 2400, 4000 and 8000 N/m/s. Frequency responses of bounce acceleration, roll angular acceleration and pitch angular acceleration to road displacement are shown in Figure 9.



(a) Bounce acceleration

(b) Roll angular acceleration

(c) Pitch angular acceleration

Figure 9 Frequency response of accelerations to road displacement (uncoupled damper)

Figure 9 indicates that the changing of the value  $c_{fr}$  influences damping characteristics of bouncing, rolling and pitching motion of a car body simultaneously.

Then, frequency responses in the case of coupled electromagnetic dampers are calculated. The condition of resistances of the proposed circuit is that one of  $R_b$ ,  $R_r$  or  $R_p$  is varied as 11.9, 8.60, 5.34, 2.74 and  $0.79\Omega$ , and the others are kept at  $5.34\Omega$ . Frequency responses of bounce acceleration, roll angular acceleration and pitch angular acceleration to road displacement are shown in Figure 10, 11 and 12.

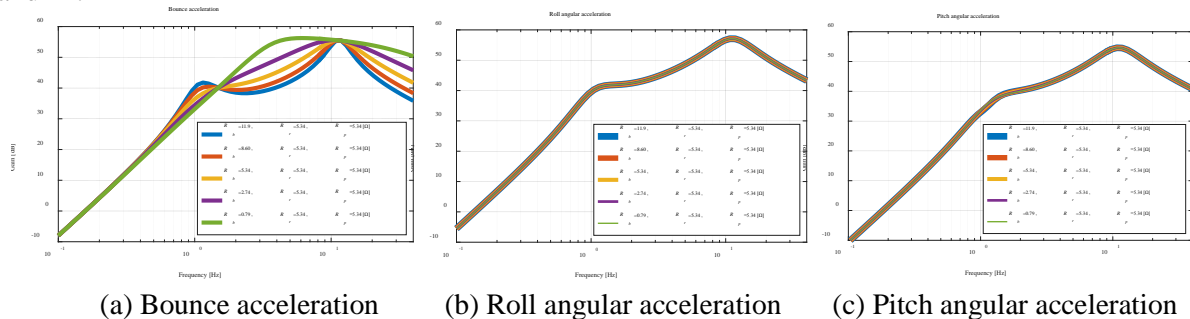


Fig.10 Frequency response of accelerations to road displacement by varying the resistance  $R_b$

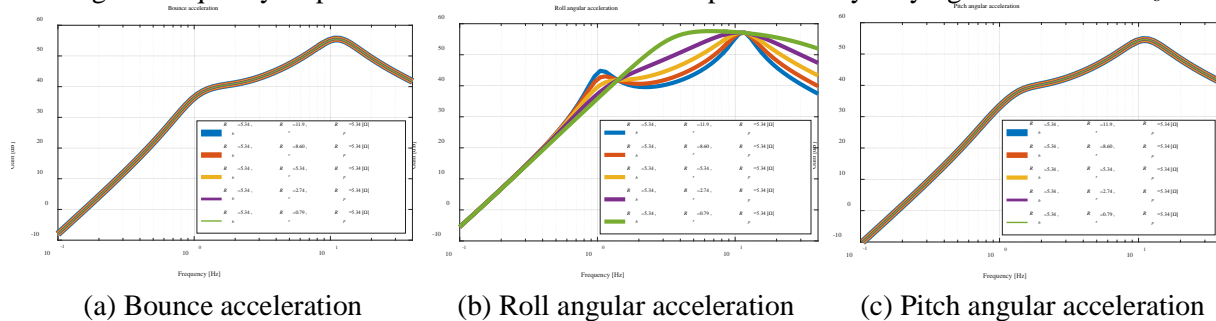


Fig.11 Frequency response of accelerations to road displacement by varying the resistance  $R_r$

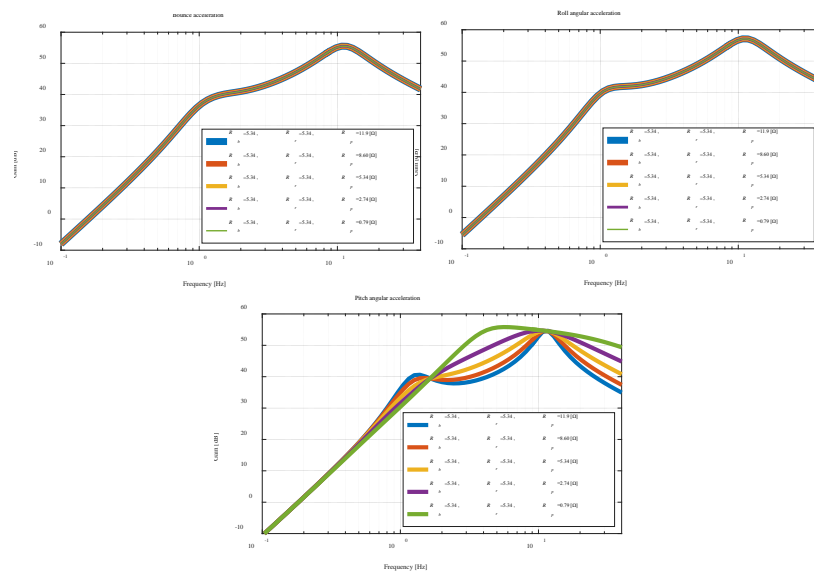


Fig.12 Frequency response of accelerations to road displacement by varying the resistance  $R_p$

Figure 10, 11 and 12 indicate that the resistance value  $R_b$  influences only the damping characteristic of bouncing motion. In the same way,  $R_r$  influences only rolling motion and  $R_p$  influences only pitching motion. Thus, it is indicated that the proposed coupling method enables the damping characteristics of bouncing, rolling and pitching motion of a vehicle to be tuned independently.

### 5.3. Anti-rolling and anti-pitching suspension system with the proposed coupling method



The behavior of the vehicle is calculated with vertical disturbances to the wheels from the road displacement, roll moment acting on the car body generated by steering and pitch moment generated by accelerating and braking. The time history of road disturbances input to the right and left wheels are shown in Figure 13.

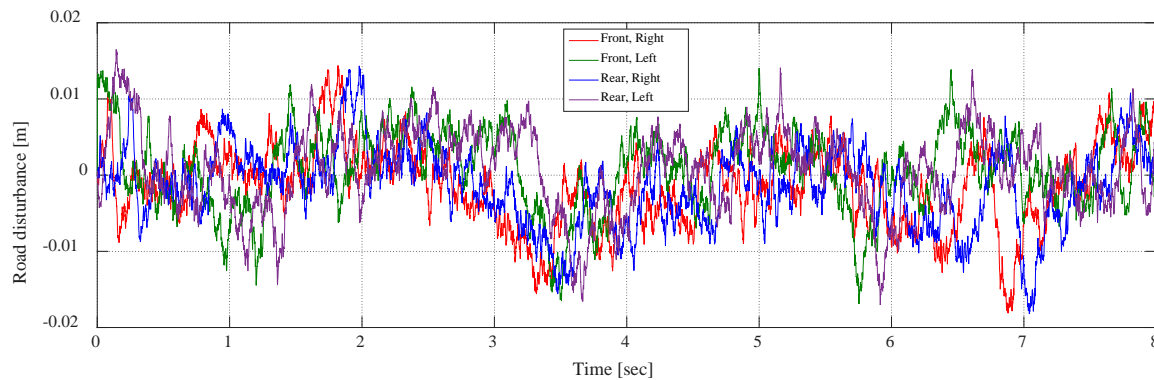


Figure 13 Road displacements

In the case where a rolling moment acts on the car body by a lateral acceleration, it is effective to use the proposed circuit and temporarily harden the damping against the rolling motion. In this paper, it is assumed that a vehicle is driving a winding road, and the forced roll and pitch moments are shown in Figure 14.

In order to obtain the same performance as normal dampers in terms of bouncing motion, the resistance  $R_b$  is kept at  $5.34\Omega$ , which realizes the same performance as the normal damper. Resistances  $R_r$  and  $R_p$  are changed from  $5.34$  to  $0\Omega$  while roll and pitch moment acts. The time history of resistance values are shown in Figure 15.

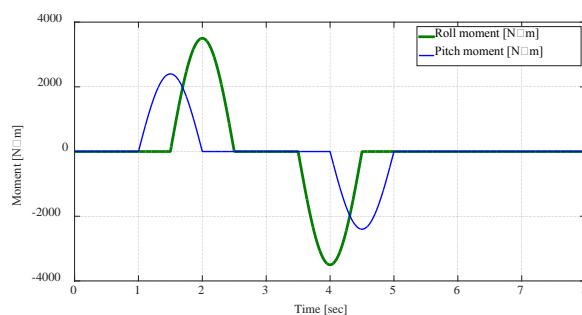


Figure 14 Forced moment

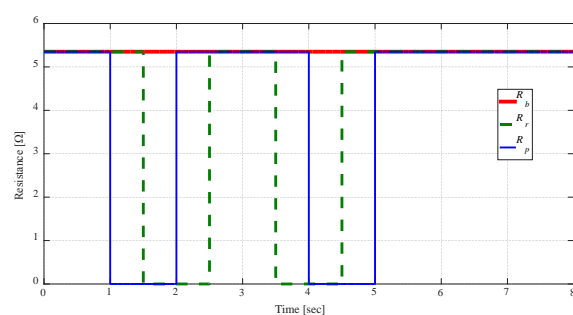


Figure 15 Time history of the Resistances

The bouncing acceleration, roll angle and pitch angle are shown in Figure 16, 17 and 18. For comparison, those in the case of normal (uncoupled) dampers are also shown.

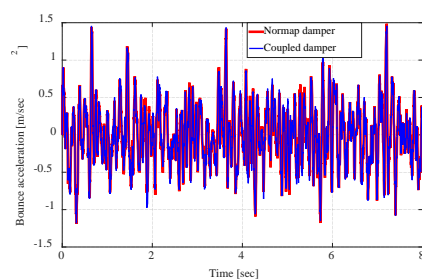


Figure 16 Bounce acceleration

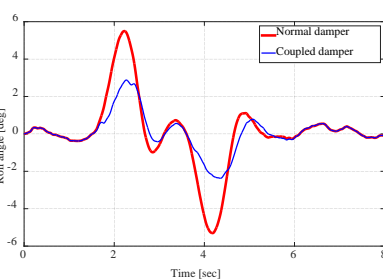


Figure 17 Roll angle

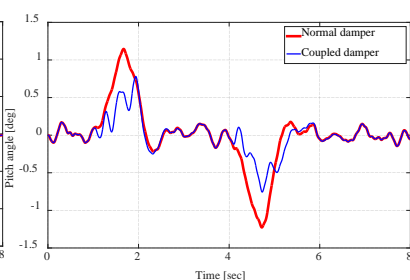


Figure 18 Pitch angle

As can be noticed from these results, the coupled electromagnetic damper reduces the rolling and pitching motion more than normal damper without leaving an effect on the bouncing motion. Therefore, these results indicate that the proposed method potentially improves the stability of the vehicle without sacrificing ride comfort.

## 6. Conclusion

In this paper, the authors proposed a coupling method of four electromagnetic dampers which enables the damping characteristics of bouncing, rolling and pitching motion of a vehicle to be tuned independently. The validity of the proposed coupling method is verified by basic experiments using four motors and proposed circuit and. The results of numerical simulations of the tuning automobile indicate the proposed system is effective.

## 7. Acknowledgement

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