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Research of Linear Electromagnet Motor Application on Automotive Suspension System

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Abstract

Vehicles are constantly being developed to provide comfortable transportation for people. This article is devoted to studying suspension systems by introducing an overview of the components that make the system, background theory, and methods of studying suspension systems using magnetic damping presented and analyzing the nature of magnetic field dampers. The suspension system always focuses on research and development to bring good handling and driving quality to the car. The suspension is intended to strengthen these elements using a weak linkage between the wheel and the body and the shock absorbers. Cars are comfortable based on passive suspension with magnetic damping to active suspension systems. The discussion is to develop a suspension system whose characteristics relate to the vehicle and the road surface. This system is under control by magnetic actuator force using the distance signal between the body car and road surface. The paper presents a study on a suspension system that simultaneously uses controlled magnetic damping to improve a car's comfort and grip.

Keywords: Magnetic damper, Semi-Active suspension system, PID controller, experimental model, frequency domain.

1. Introduction

The electromagnetic suspension system is an active electromagnetic suspension system for improving vehicle dynamics. There are new suspension systems called electromagnetic suspension systems. They are improving vehicle dynamics stability, maneuverability by using active roll control and elevation control under cornering, braking, and eliminating the influence of road when the car is turning. For safety of vehicles, the comfort of passengers, and smoothness for the driver, the suspension uses permanent magnets that interact with the passive electric coil. The suspension is reduced, independently absorbs bumps from the road surface, and returns to a balanced position quickly while the tires remain in contact with the road surface. Researchers have built a model to investigate the effectiveness of the magnetic suspension system. However, the basis and details of the control program of the suspension have not been clearly shown [1].

Stability control of an active electromagnetic suspension is simulated and calculated as a controller developed for an electromagnetic suspension used on the vehicle model ¼. Improving comfort by traveling with the suspension or handling, the suspension system achieves actuator impact force with active suspension versus passive suspension. The difference between measurements and simulations is explained by static friction in the active suspension, which consumes 80% less power than the hydraulic system. The study presents the results and evaluates the results after implementing system control. The author starts from the vehicle dynamics equation, then goes to the factors affecting the joystick and gives an overview of the control program. The factors measure the efficiency when the electromagnetic system operates [2].

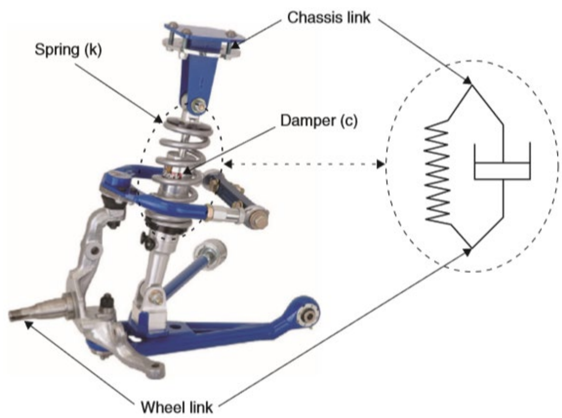

Fig. 1. The classical scheme of a wheel-to-chassis suspension in a car.

A controller design with the two factors of comfort or handling focus to analysis spring and damper of the suspension system is shown in Fig. 1. Simulation shows the performance and achievable efficiency of the electromagnetic suspension system. Research shows an improvement in comfort constrained by suspension travel or handling as determined by achievable actuator force with active suspension versus passive suspension. The difference

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between measurements and simulations is explained by static friction in the active suspension. The study presents the control factors, the basis, and the control method. However, it shows that the control program's content is not fully displayed to serve the source.

Electromagnetic suspension is a new technology with great potential and is being researched and developed by many researchers and automakers. However, the organizations have not announced it yet, so it is still a big question. In addition, there is a little research project on the electronically controlled electromagnetic suspension system in Vietnam. There are still many difficulties in accessing reliable information sources. This paper aims to choose and study the electronically controlled electromagnetic suspension system. The study is based on the traditional suspension system and add a new modern suspension system. Thereby, the research is design and manufacturing of the controlled electromagnetic suspension system called LEM (Linear Electromagnet Motor)

The active suspension can compromise two things of suspension needs: comfort and handling riding. Research showed that a car would have good ride comfort in the passive suspension system, then it has a lousy handing ride in tire deflection and reverts. This paper will share a study on a controlled suspension system, in which we apply the theory of magnetic force.

2. Research Methodology

2.1. Passive Suspension System

A passive suspension system is the most common suspension system and it is widely used. This study will analyze it to find the required properties of a suspension system.

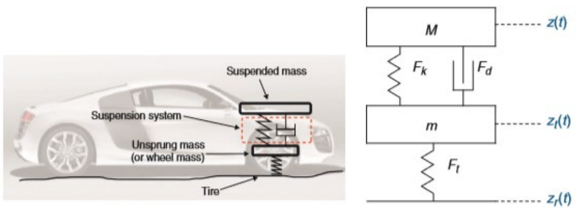

Fig. 2. Quarter-car representation of a suspension system in a vehicle.

A suspension includes springs, shock absorbers, and links that connect the sprung mass (the body) with un-sprung mass (wheels) and allow relative movement between the two. The parameters of the suspension system include body mass (M); the ratio or constant spring (F_k); the damping ratio of damper (F_d); road surface profile (z_t); tire mass (m), and constant spring of tire (F_t).

When the vehicle enters a bend, accelerates, or goes through an uneven road, distance between the wheel and the body will change due to acceleration. The transmission weight of the body is variable. The spring length of the suspension will change and create elastic oscillations because of the car oscillation. This oscillation reduces driving quality, but the dampers suppress this oscillation and bring the vehicle to a steady-state after a specific time.

Every vehicle will have at least one suspension for each wheel position in contact with the roadshow as shown in Fig. 2. Therefore, the suspension systems have the main components: springs, dampers, and connecting rods. This research will analyze such a system to describe it with mathematical equations [3].

The equation describing the alignment of the suspension is a system of differential equations:

$$\begin{cases} M\ddot{z}(t) = F_k(t) + F_d(t) - Mg \\ m\ddot{z}_t(t) = -F_k(t) - F_d(t) + F_t(t) - mg \end{cases} \quad (1)$$

Equation (1) represents a dynamic system of the suspension system. The equation of passive suspension systems requires the following additional conditions:

$$\begin{cases} F_k.x \geq 0 \\ F_d.\dot{x} \geq 0 \\ x = -(z - z_t - L) \end{cases} \quad (2)$$

where x is the spring's modified length, L is the spring's natural length when the spring is not subjected to any external force, i.e. $F_k = 0$, when $x = 0$.

The characteristic quantities for springs and dampers are the spring force F_k and the damping force F_d depending on the variation of x.This relationship is described by equation (3). The spring force F_k depends on x, but the damping force depends on the derivative of x.

$$\begin{cases} F_k = k.x \\ F_d = c.\dot{x} \end{cases} \quad (3)$$

From this point of view, the cause of the car's oscillation is the elastic force of the spring. It is a soft coupling used in the suspension to help the wheels grip the road better. Nevertheless, then the spring also accumulates elastic energy, this energy creates an elastic force acting on the vehicle's body, causing the body to vibrate. Body vibrations affect the driver, cargo, and other vehicle components. The oscillation also affects the wheel's pressure on the road surface. If it is large enough, it makes vehicle uncontrol and unsafety.

The shock absorber is arranged parallel to the spring as shown in Fig. 2. When the spring changes length due to oscillation, it does the shock absorber. The spring's elastic force pressurizes the liquid oil in the dampers and forces them to pass through the orifice, creating drag. Therefore, the spring's oscillation will gradually decrease depending on the magnitude of this resistance. From an energy point of view, the elastic energy of the spring is converted into heat by the work of the frictional force generated in the oil damper.

A suspension system is made with elastic energy is ultimately converted into heat energy released to the environment. Fig. 3 depicts the ideal behavior of dampers and springs by balancing the elastic force as the damping resistance.

The elastic energy is subtracted by the frictional resistance of the shock absorber. The frictional resistance force of the shock absorber depends on the rate of change of the distance between the vehicle body and the wheel, which changes the length of the spring and shock absorber and affects the oil flow velocity in the shock absorber. Both road holding/handling and riding quality are at odds. Since road holding/ handling needs a small resistance force of damping and a large elastic force of spring. The tuning of suspension involves finding the right way.

It is difficult to support both road holding and riding quality at the same time when the car uses a passive suspension using oil damping. Recent studies have shown that a suspension that can support these two factors needs to be controlled, typically as a semi-passive or active suspension. These suspension systems are added to automatically control the damping resistance and even the elastic force of the springs to help the car satisfy these two factors simultaneously.

Next, the quarter-car suspension is analyzed to show the above two factors' parameters. One or more parameters are selected to study a controlled suspension system supporting road holding and riding quality. [3]

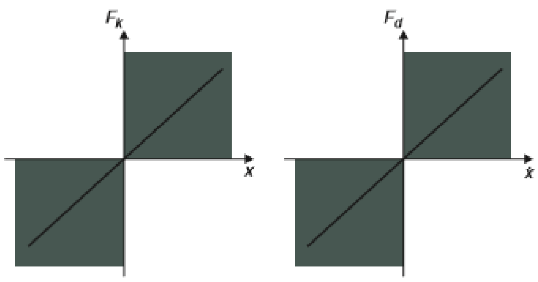

Fig. 3. Pictorial representation of the suspension "passivity constraint."

The riding quality of a car is achieved when the coefficient c is small in compression. The significance in expansion damping resistance is proportional to coefficient c. The holding of the wheel is acquired when the coefficient c is in the effective compression process and the small expansion process. However, the damping coefficient c of the passive suspension is a constant, so it can be concluded that the riding quality and the holding of wheels are at odds. So, the damping coefficient c or damping resistance must be adjusted [4].

2.2. Theory of Electromagnet

The controlled damper is a type of damping that controls the resistance produced. The damping force is controlled by an electrical signal, which will follow the controller's command. Two necessary factors are the quality of driving and the ability to grip the car's road. The damping resistance is created most suitably so that the vehicle's body is less shaky and the wheels still grip the road well. The magnetic force between the coil and an adequately placed permanent magnet can act as damping resistance as shown in Fig. 4. This force is controlled by the magnitude of the current flowing through the coil. Indeed, this magnetic force is like the resistance of an oil damper. It is an advantage because it can be controlled [5]

The magnetic force can be reversed when the direction of current flowing in the coil is changed. The magnitude of the current determines the magnetic force. Therefore, magnetic resistance can replace the resistance of oil shock absorbers. The current passing controls the allowable magnetic force through the coil. Dissipated electrical energy will be converted into mechanical energy causing the spring to fade. This oscillation will be minimized when the magnetic force is adjusted appropriately [6]

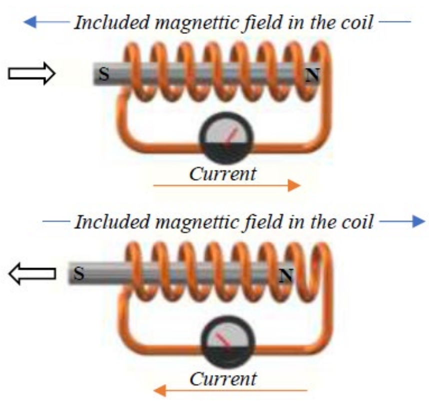

Fig. 4. A type of electromagnet which is to generate a controlled magnetic field

Elastic energy is converted into heat/electrical power loss in the coil (electromagnet). Due to the thermoelectric effect - (Peltier_Seebeck), electrical capacity is calculated in $P = u(t).i(t)$. The magnetic force's damping will increase the car's ability to compromise the two factors of holding wheels and driving quality.

2.3. PID Control

The elasticity is made by oscillation between the body car and the wheel. This oscillator is a damped oscillation because the mechanism itself has internal friction. A suspension system is the flexible link that connects a vehicle to its wheel, allows relative motion between the two, and avoids significant shocks. An electronic filter will remove the noise signal. There are different types of the road surface. In different driving situations, a suspension system must keep the wheels on the road while keeping body vibrations as less as possible. The shock absorber needs to eliminate the vibrations caused by the spring and not make the connection too stiff. The damping resistance needs to be changed accordingly in the different driving conditions. That was hard to achieve with a passive suspension system.

The damper system requires a control unit, which can control the resistance of the damper following the driving condition. Therefore, the controller must know when to change the damping resistance. The magnitude of the force and its direction of effect needs to be controlled. The selected PID controller (Proportional Integral Derivative) is a proportional differential controller and a feedback loop control mechanism, and it is the most used controller in feedback controllers. A PID controller continuously calculates an error value *e(t)* as the difference between the desired setpoint (SP) and a measured process variable (PV) and applies a correction based on proportional, integral, and derivative terms (denoted P, I, and D respectively).

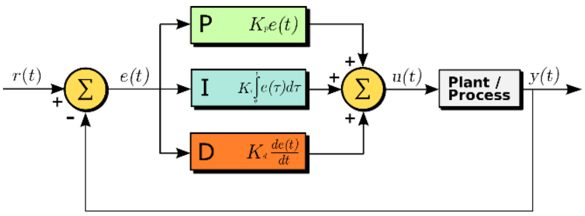

Fig. 5. A block diagram of a PID controller in a feedback loop r(t) is the desired process value or setpoint (SP), and y(t) is the measured process value (PV).

The controller's PID algorithm restores the oscillation signal from the sensor to the desired signal with minimal delay and overshoot by controlling the magnetic force of the magnetic damper affecting the suspension system. The distinguishing feature of the PID controller is the ability to use the three control terms of proportional, integral, and derivative influence on the controller output to apply accurate and optimal control. The block diagram in Fig. 5 shows how these terms are generated and applied. It shows a PID controller, which continuously calculates an error $e(t)$ value as the difference between the desired setpoint $SP = r(t)$ and a measured process variable $PV = y(t)$: $e(t) = r(t) - y(t)$, and applies a correction based on proportional, integral, and derivative terms. The controller attempts to minimize the error over time by adjusting a control variable $u(t)$, such as opening a control valve, to a new value determined by a weighted sum of the control terms.

The PID control scheme is named after its three correcting terms, whose sum constitutes the manipulated variable (MV). The proportional, integral, and derivative terms are summed to calculate the output of the PID controller. Defining $u(t)$ as the controller output, the final form of the PID algorithm is:

$$u(t) = MV(t) = K_p.e(t) + K_i\int_0^t e(\tau)d\tau + K_d\frac{de(t)}{dt} \tag{4}$$

where:

K_p is the proportional gain, a tuning parameter,

K_i is the integral gain, a tuning parameter,

K_d is the derivative gain, a tuning parameter,

$e(t) = SP - PV(t)$ is the error (*SP* is the setpoint, and *PV(t)* is the process variable),

t is the time or instantaneous time (the present),

τ is the variable of integration (takes on values from time *0* to the present t).

Equivalently, the transfer function in the Laplace domain of the PID controller is:

$$L(s) = K_p + \frac{K_i}{s} + K_d.s \tag{5}$$

where *s* is the complex frequency.

Tuning a control loop is the adjustment of its control parameters (proportional band/gain, integral gain/reset, derivative gain/rate) to the optimum values for the desired control response. Stability (no unbounded oscillation) is an essential requirement, but beyond that, different systems have different behavior, different applications have different requirements, and requirements may conflict with one another. The PID tuning is a complex problem, even though there are only three parameters. In principle, it is simple to describe because it must satisfy complex criteria within the limitations of PID control shown in Fig. 6. Accordingly, there are various methods for loop tuning, and more sophisticated techniques are the subject of patents.

This section describes some traditional manual methods for loop tuning. Designing and tuning a PID controller appears to be conceptually intuitive but can be challenging in practice if multiple (and often conflicting) objectives such as short transient and high stability are achieved. PID controllers often provide acceptable control using default tunings, but performance can generally be improved by careful tuning, and performance may be unacceptable with poor tuning. In this study, a PID controller is used to control the damping resistance to the suspension. Controller parameters *P, I, D* are adjusted repeatedly through computer simulations until the closed-loop system performs or compromises as desired for stability amplitude as shown in Fig. 7 after calculating. The PID controls current in magnetic resistance to change damping force. It will support both road holding/ handling and riding quality [7-10].

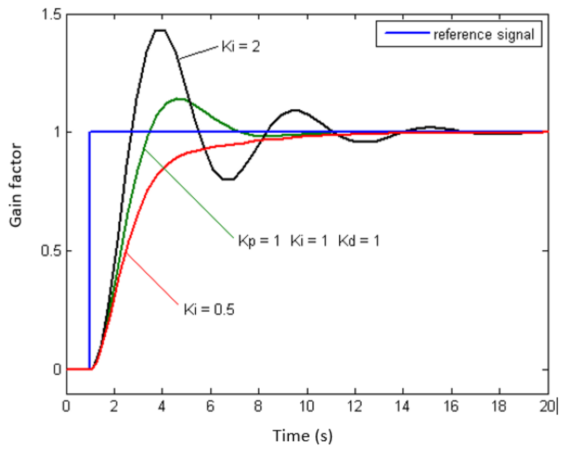

Fig. 6. Response of PV to step change of SP in time

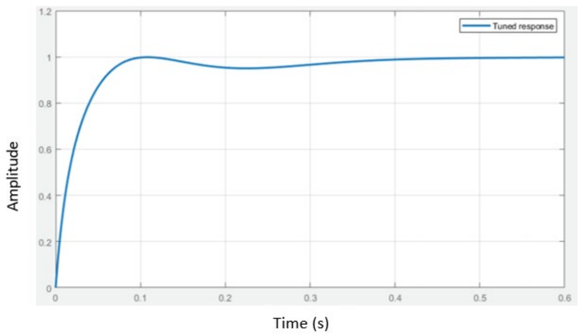

Fig. 7. Parameter adjustment window for PID controller using MATLAB software with controller parameters (*P*=2.122, *I*=30.25, *D*=0.0229, *N*=66.66, *b*=1, *c*=1)

3. Experimental, Results and Discussion

3.1. Suspension Modeling

The coefficient of elasticity of the wheel is quite significant, so consider the wheel to be rigid and always stick to the road surface. The aim is to simplify the simulation model. Currently, the suspension system only includes the mass representing the body, the spring, the magnetic damping, and the function describing the road surface. The following differential equation describes the suspension model:

$$M.\ddot{z} = F_k(t) + F_d(t) - Mg \quad (6)$$

The purpose of the simplification for suspension modeling is to make it easier to model test items for evaluation.

3.2. Electronic Suspension Modeling

The suspension model in the study uses dampers, which use magnetic forces to reduce vibrations. From (6), replace the friction force (oil) with the magnetic force (controlled), we can rewrite the equation as follows:

$$M.\ddot{z} = F_k(t) + F_m(t) - Mg \quad (7)$$

A suspension uses a controlled magnetic force which the PID controller will control. This force compromises road holding/handling and riding quality. Hence, the controlled magnetic force must satisfy the following conditions:

$$F_m \geq 0 \quad (8)$$

The magnetic force is calculated as follows:

$$F_m(t) = -B_{(t)}.I_{(t)}.L \quad (9)$$

B is the flux appearing in the coil core, *L* is the coil's inductance, and *I* is the current flowing through the coil, which the PID will control.

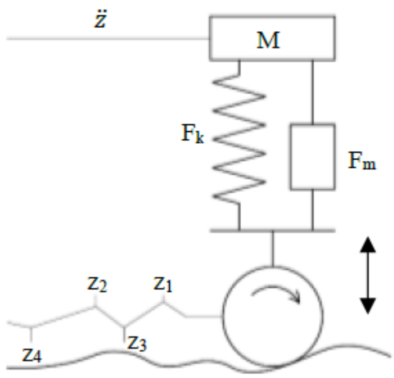

Fig. 8. Diagram of suspension system applied magnetic field

where: $B = \frac{\mu_0 NI}{l}$ (10)

in which:

B is the magnetic field density, the flux appearing in the coil core

l is the length of the coil,

μ_0 is the constant of inductance,

N is the number of rings turns,

I is the current through the coil

The goal of controlling the magnetic force of the suspension using magnetic dampers is to keep the body vibrations as small as possible, and the wheels still must grip the road. Hence, the equation must approach zero.

$$M.\ddot{z} = F_k(t) + F_m(t) - Mg \cong 0 \quad (11)$$

The left-hand side of the equation describes the acceleration of the body vehicle, which approaches zero when the magnetic force is controlled approximately by the elastic force of the spring [11]. Magnetic force is controlled so that the acceleration of the vehicle body oscillates as little as possible around a value that is considered smooth. Indeed, a suspension using magnetic forces will compromise these two factors. Fig. 8 shows a model of a suspension using magnetic force. F_m is the magnetic force, F_k is the elastic force of the spring, the wheel always grips the uneven road surface, and the superior acceleration of the body is zero.

3.3. Suspension System Model

The experimental model of the suspension system using controlled magnetic force is described above. There are a representative mass of the body, springs, magnetic damper, uneven road surface regeneration mechanism, and the frame structure of the model. We designed a new model as shown in Fig. 9 and made an experimental model as shown in Fig. 10. The experimental results of the suspension model using the magnetic field are the set of control parameters of the PID. It is the most suitable for a controlled suspension system to satisfy the two factors of traction and driving quality.

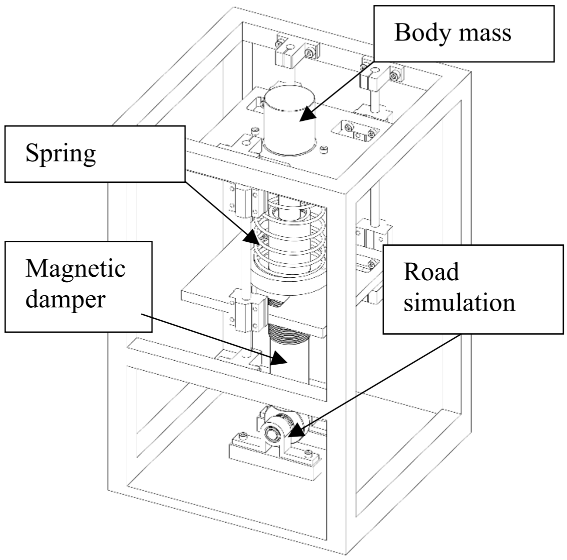

Fig. 9. A prototype of active suspension systems

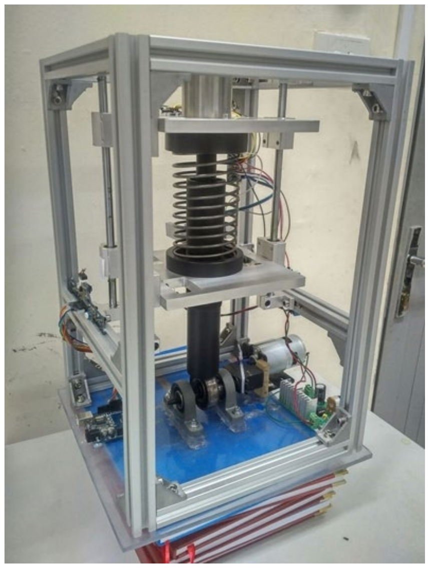

Fig. 10. The experimental model of active suspension systems

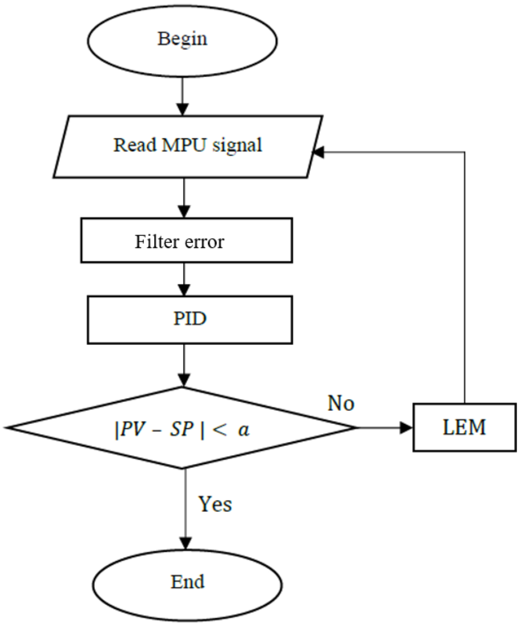

Fig. 11. Flowchart of control for experiment model of semi-active suspension system applied Linear Electromagnet Motor.

3.4. The Electronic Suspension Control Unit

3.4.1. The Magnetic Damper Control Unit

The magnetic damping force is controlled by an Arduino with a PID controller, which allows reading the acceleration signal of the suspended block and process to issue the current control command to the magnetic damper. A power control unit uses current control for the coil. This control unit is called a power circuit (H-bridge circuit) that will receive the control commands of the Arduino unit.

3.4.2. The Magnetic Damper Control Program

The program logic to control the magnetic damper is described as a flowchart shown in Fig. 11.

1. MPU sensor 6050 reads the acceleration value of the hypothetical vehicle body.

2. Acceleration value is filtered, eliminating sensor error.

3. Acceleration value is compared with a set value.

4. If the comparison result is out of the allowable range, the PID will send a control signal to the H-bridge circuit, which controls the current to the magnetic damper so that the acceleration signal is within the allowed range.

5. The program ends if the comparison result is within the allowed range.

In this study, the suspension system uses the magnetic damper controlled by a PID controller, Linear Electromagnet Motor (LEM). The control program will repeat the measurement and control process. The acceleration value of the body is always within the allowable range. The PID parameters K_p, K_i, K_d will be adjusted so that the control system works best with the suspension model.

3.5. Results Analysis

Acceleration oscillation of car body reduced 92.3% with LEM activated compared with passive damper, which has presented a dotted line and solid line, respectively, as shown in Fig. 13. The results have experimented on the experimental model of semi-active suspension systems. The model is set up with parameters, as shown in Table 1.

The suspension test performs two operating modes of the LEM with active and inactive states. The model is treated as a passive suspension with the model's internal load friction. Indeed, for a sufficiently small model, this value is acceptable. Moreover, the magnetic damper is active. The PID controller controls the magnetic force. The acceleration of the car body is assumed to be within the allowable range. Fig. 12 shows that under the system's frequency response, the maximum value of acceleration intensity oscillation of the car body reached 2.5 Hz. With the road, simulation was set up sinusoidal oscillation with 10 mm of amplitude and 2.5 Hz of frequency. The value of the car's body acceleration intensity oscillation with LEM and passive damper are 5 and 65, in respectively. They have thirteen times different. It was shown that the acceleration has reduced when applying LEM to the model of the suspension system. The occurrence of small peaks at other frequencies is explained as the model's noise. It depends on many factors such as sensor noise, model fitting tolerance, model elasticity, etc.

Table 1. The parameters of the experimental model of semi-active suspension systems

Basic parameters	Value	Unit
Mass of car body simulated	1.6	Kg
Frequency of road simulated	2.5	Hz
The amplitude of road simulated	10	mm
P	2.122	const
I	30.35	const
D	0.0229	const
Power	19.5	Volt
Current	3.46	ampere

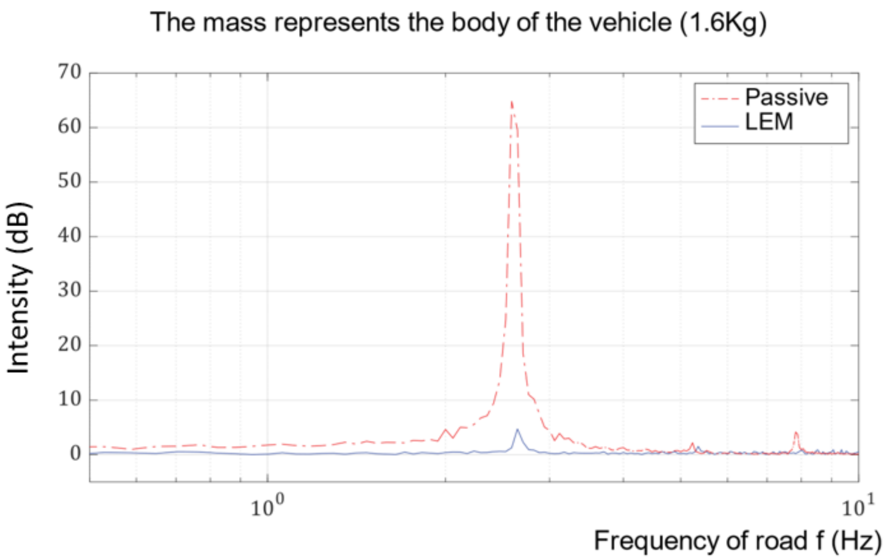

Fig. 12. Body acceleration intensity is represented in the frequency domain.

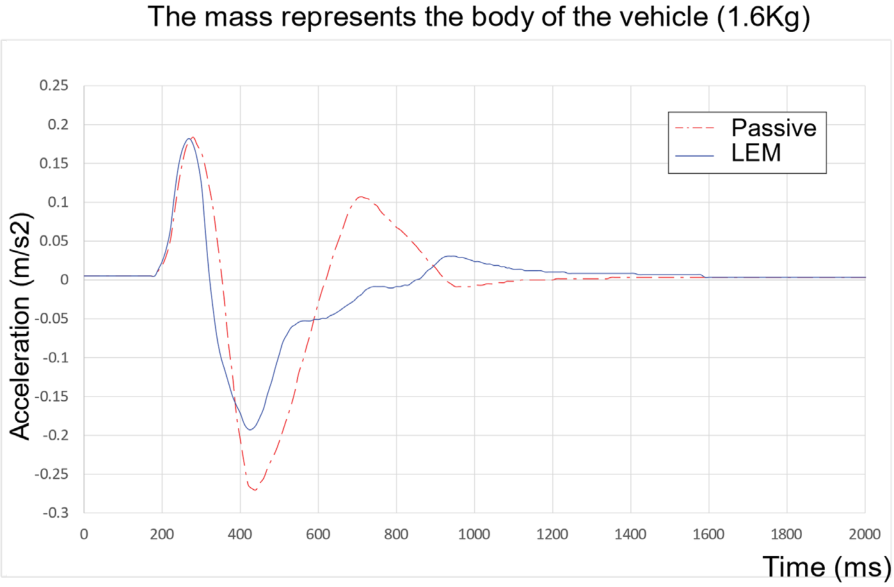

Fig. 13. The vehicle body acceleration with step excitation in the time domain.

Fig. 13 shows the oscillation acceleration of a sprung mass in the time domain with impulse excitation. The red line describes the inactive LEM mode, when the system is excited and oscillates with an average acceleration of 0.34 m/s^2. The blue rapid line describes when the LEM is active, the average acceleration system average is reduced to 0.25 m/s^2. The system with LEM in semi-active suspension has about 30% reduction in peak acceleration and overall lower than in passive suspension. The LEM applied force to the suspension to reduce vibrations of sprung mass in the quarter-car model. It is affected by the control speed of the controller is used in the experimental model of semi-active suspension systems.

4. Conclusion

The experimental model uses controlled magnetic damping. The current flowing through the coil causes inductance so that the coil may heat up after a while. This heat reduces the magnitude of the magnetic force. The PID controller parameters, *P, I, D* need to be adjusted when changing the mass *M* assumed for the mass of the vehicle body because the change of *M* causes the properties of the system to change.

From the basis to the results of the suspension test model, we can see that: the suspension system using magnetic shock absorbers can simultaneously compromise the two factors of traction and smoothness for the car. The result showed that the LEM suspension acceleration peak point reduces about 30% and total lower than passive suspension. This study highlights the potential for suspension systems using magnetic dampers in the future.

Acknowledgments

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References

[1] Bart L. J. Gysen; Johannes J. H. Paulides; Jeroen L. G. Janssen; Elena A. Lomonova, Active electromagnetic suspension system for improved vehicle dynamics, IEEE Transactions on Vehicular Technology, Volume 59, Issue 3, March 2010. https://doi.org/10.1109/TVT.2009.2038706

[2] T.P.J. vander Sandea, B.L.J. Gysenb, I.J.M. Besselinka, J.J.H. Paulidesb, E.A. Lomonovab, H. Nijmeijera, Robust control of an electromagnetic active suspension system: Simulations and measurements, Mechatronics, Volume 23, Issue 2, Pages 204-212, March 2013. https://doi.org/10.1016/j.mechatronics.2012.07.002

[3] SergioM. Savaresi, Charles Poussot Vassal, Crist, Semi-Active Control Design for Vehicle. The Boulevard, Langford Lane, Kidlington, Oxford, OX5 1GB, UK, Elsevier Ltd 2010, pp. 232

[4] Carlos A. Vivas-Lopez, Diana Hernández-Alcántara, Manh-Quan Nguyen, Ruben Morales-Menendez, Olivier Sename, Force control system for an automotive semi-active suspension, IFAC, Volume 48, Issue 26, 2015, Pages 55-60 https://doi.org/10.1016/j.ifacol.2015.11.113

[5] Zepeng Gao, Sizhong Chen, Yuzhuang, Zhao Zheng Liu, Numerical evaluation of compatibility between comfort and energy recovery based on energy flow mechanism inside active electromagnetic suspension, Energy, Volume 170, pp. 521-5361 March 2019. https://doi.org/10.1016/j.energy.2018.12.193

[6] Mahmoud Omar, M.M. El-kassaby, Walid Abdelghaffar, Parametric numerical study of

electrohydraulic active suspension performance against passive suspension, Alexandria Engineering Journal vol 57, pp. 3609–3614, 2018. https://doi.org/10.1016/j.aej.2018.05.007

[7] Gokul Prassad S, Malar Mohan K, A contemporary adaptive air suspension using LQR control for passenger vehicles, ISA Transactions Volume 93, pp. 244-254, October 2019. https://doi.org/10.1016/j.isatra.2019.02.031

[8] Ashkan Keivan, Brian M. Phillips, Rate-independent linear damping in vehicle suspension systems, Journal of Sound and Vibration vol 431, pp. 405-421, 2018. https://doi.org/10.1016/j.jsv.2018.05.037

[9] A. J. Nieto, A. L. Morales, J. R. Trapero, J. M. Chicharro, P. Pintado, An adaptive pneumatic suspension based on the estimation of the excitation frequency, Journal of Sound and Vibration vol 330, pp. 1891–1903, 2011. https://doi:10.1016/j.jsv.2010.11.009

[10] M.M. Moheyeldein, Ali M. Abd-El-Tawwab, K.A. Abd El-gwwad, M.M.M. Salem, An analytical study of the performance indices of air spring suspensions over the passive suspension, Beni-Suef University Journal of Basic and Applied Sciences vol 7, pp. 525–534, Dec 2018. https://doi.org/10.1016/j.bjbas.2018.06.004

[11] Y. Guoa, Z. Linga, A magnetic suspension spindle system for micro EDM, Science Direct. 18th CIRP Conference on Electro Physical and Chemical Machining, CIRP 42, 2016, pp. 543 – 546. https://doi.org/10.1016/j.procir.2016.02.248