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Definition, criteria and approaches in designing suspension system with active controls

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Abstract. Comfort and good handling are always a problem in conventional passive suspension systems. The ideal suspension criterion is to have a short time response, have a small amplitude and eliminate the frequency of causes of motion sickness. The system is only obtained with an active suspension system. The active suspension has an actuator that is able to produce a force to reduce the dynamic force of the vehicle. This actuator will be controlled by a PID active control. The test results showed that the active control was able to reduce the amplitude by 18 mm, passes the Sickness motion frequency and can return to the set point in 0.8 seconds.

1. Introduction

The suspension is a part of a vehicle that affects the dynamics and comfort of the vehicle. Suspension development is always related to vehicle development. Vehicles are getting faster and the distance is getting farther away, making the role of the suspension become increasingly important. So that vehicle designers see the suspension to be one of the important components to produce a vehicle that is fast, comfortable and safe.

The beginning of the vehicle does not use suspension, so the frame of the vehicle is directly connected to the wheel. The history of suspension use is not specifically recorded but is directly related to the development of the vehicle. The possibility of suspension appeared when the vehicle was found with the double pivot steering system in 1893 [1]. When the chain drive system begins to be replaced with an axle system on the rear of the vehicle, it will increase the unsprung mass. Increasing the unsprung mass at the rear of the vehicle requires making better damping.



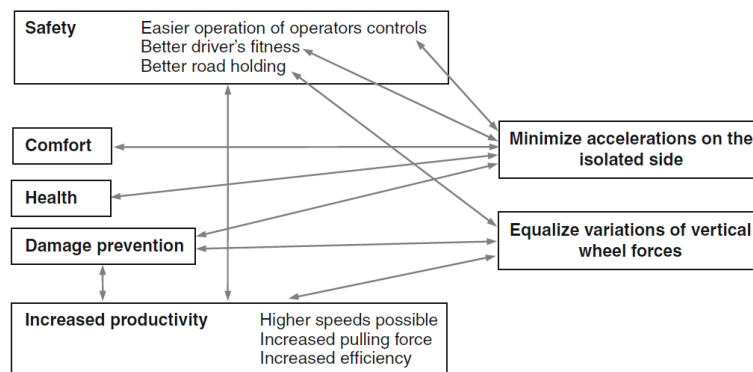


Figure 1. Task and function for suspension system [2].

The suspension system of the vehicle is a collection of mechanical components that are connected to the frame or body of the vehicle. There are three basic components of the suspension, namely linkages, spring and shock absorbers (dampers) [3]. Linkages in vehicles are usually called links because it functions as a liaison between the suspension and the frame or body of the vehicle. The number of links on a vehicle can differ depending on the type of suspension and vehicle. Spring has a different type in each suspension system, including coil, leaf and torsion bar. The type of coil in the form of coil that is most widely used in vehicles, especially small vehicles. The damper on the suspension system usually uses pistons and cylinders with a valve that can be adjusted by hydraulic or pneumatic pressure.

The suspension system has actually become a part of driving life, but many people are not aware of its existence. There are five tasks and functions of the suspension system on the vehicle, including safety, comfort, health, damage prevention and increased productivity [2]. The relationship between the five tasks and functions of the suspension system can be seen in Figure 1. If the five tasks and functions of the suspension system are met, it can be said that the suspension system is the ideal condition of the suspension.

The ideal conditions of suspension cannot be achieved only with conventional suspension systems with a constant damping coefficient [4]. The constant damping coefficient makes conflict occur in determining good handling or driving comfort. If you want to drive comfort to be more important, than handling the vehicle becomes unsteady. The relationship between the two problems can be seen in Figure 2.

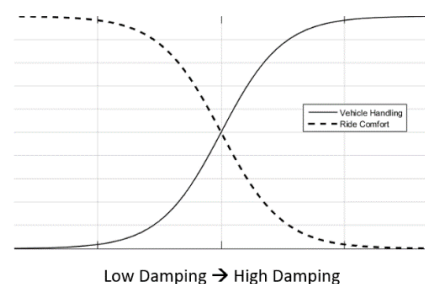


Figure 2. Handling vs comfort with damping ratio.

2. Ideal Suspension Criteria

The first criterion of an ideal suspension is driving stability, this is the first because it involves safety in driving. The role of the suspension in driving stability is to control the vehicle as soon as possible in its reference position after experiencing disturbance. The disturbance can be in the form of road conditions or dynamic motion of the vehicle.

The first criterion cannot be solved only with conventional passive suspension, this is because the damper ratio of the passive suspension is constant, it can be seen in Figure 3a. In early 1974, Karnopp introduced a semi-active suspension with sky-hook control [5]. Semi-active suspension work system can be seen in Figure 3b. Suspension with an actuator that is able to be fully controlled between sprung and unsprung masses, this suspension is also referred to as an active suspension [6]. Preliminary studies on the performance of active suspensions have been conducted by Hrovat [7].

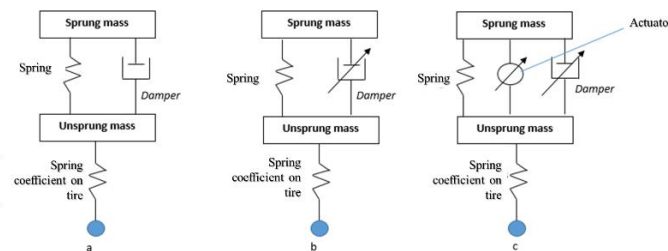


Figure 3. Classification from the suspension system.

The second criterion is health. In addition to the motion sickness described in the introduction, the vehicle can also experience head toss. Head toss can occur when the drive wheel passes through a deep hole. Head toss effect occurs because the receptors of 3 orthogonal oriented channels in each inner ear are activated by the acceleration of the head angle [8]. Head toss occurs if the vehicle enters a frequency of 2-8 Hz. Motion sickness and head toss are produced when the vehicle experiences low frequency. This frequency needs to be eliminated in the vehicle. In addition to frequency, the amplitude generated also needs to be reduced.

The third criterion is driving comfort. These criteria can be obtained by eliminating the high frequency and high amplitude on the vehicle. This high frequency can occur when a vehicle has a suspension with a large damper coefficient. A large damper coefficient makes handling in driving better, but the large frequency it produces makes passengers uncomfortable. The three criteria above are the basis of how to design the ideal suspension so that the vehicle becomes more safe, comfortable and speeds faster.

3. Ideal Suspension Approach

The three ideal suspension criteria can be applied if the damper is not constant and has an actuator to find out the ideal position of the vehicle. These criteria can use active suspension to approach the ideal suspension. Inactive suspension there is an actuator that can produce a force to resist vibrations in the vehicle.

Actuators that are often used as active suspension research subjects are hydraulic and electromagnetic. Both types of actuators have advantages and disadvantages to each. The advantage of a hydraulic suspension system is a large force density, easy to design, reliable and more mature to be commercialized. While the disadvantages of the active hydraulic suspension system include: it requires a continuous compressive system, leakage, and pollution. When compared with a hydraulic suspension system, the advantages of an electromagnet system are to increase dynamic behaviour, increase stability and increase efficiency [9]. Electromagnetic suspension systems have the potential to create an ideal suspension system.

Apart from the actuator, the suspension system must also have a spring and damper. The ideal spring condition is spring without friction, has no mass and moves linearly. Great force is needed at each end to hold the ideal spring when stretching from $|\Delta x|$ given from $F_{applied} \equiv k|\Delta x|$ where k is the spring constant in N/m . So according to Hooke's law, the idea of spring is

$$F_{OS,x} = -kx \quad (1)$$

where $F_{OS,x}$ is 1 vector dimension that is in contact with the force on an object (vehicle). So if the force received by the car and then make the x position change, the value of k will adjust the force. $F_{OS,x}$ can also be obtained from the vertical force on a moving vehicle.

The damper is also one part of the suspension system. Together with the spring, the damper works to reduce shocks or vibrations in the vehicle caused by road conditions or dynamic motion of the vehicle. If the spring and damper are combined into a suspension system, we can get an equation that is in accordance with Newton's second law. The equation is combined with equation (1) to be:

$$F_{OS,x} = -kx - b \frac{dx}{dt} \quad (2)$$

where M is the mass of the vehicle and b is the coefficient of the damping element.

The ideal suspension system of the vehicle can only be obtained with feedback from the sensor to change the damper value and the spring constant. Feedback can be done by adding the accelerometer sensor to the suspension system. Damping values and spring constant changes are obtained from changes in force on the vehicle. The force that changes is read by the sensor in the form of data. Then the data will determine the constant value of the spring and damping. In the mathematical model the equation that occurs in the accelerometer is:

$$M \frac{d^2x}{dt^2} + b \frac{dx}{dt} + kx = M \frac{d^2a}{dt^2} \quad (3)$$

In order to be modeling, equation (3) is converted into Laplace transform, so obtained:

$$Ms^2X(s) + bsX(s) + kX(s) = -MA(s) \quad (4)$$

Where $X(s)$ and $A(s)$ is the Laplace transform of $x(t)$ and d^2y/dt^2 , so to get value $X(s)$ is obtained:

$$X(s) = -\frac{MA(s)}{Ms^2 + bs + k} \quad (5)$$

4. Research Method

An ideal suspension can be obtained if it meets the requirements if the spring constant and the damping value meet the equation (1) and (2), other than that it must be able to change the spring constant and damping as the force changes in the vehicle. The addition of active control in the suspension system that is able to change the damping value will produce minimal vibration to the vehicle. The suspension system that does not have active controls to change the damping value can be seen in Figure 4. In figure 4 it can be seen that the suspension system has difficulty reaching the reference position.

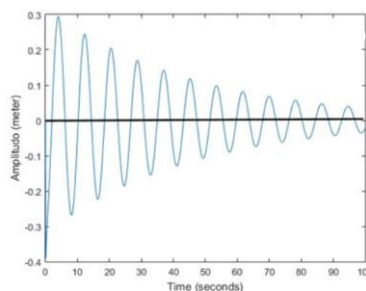


Figure 4. Vehicle position changed due to disturbance [10].

PID controller used in this suspension system. The advantages of using PID controllers include good stability, simple design and easy application on hardware [11]. because of these advantages the PID controller is widely used in the industrial world. PID control also has a disadvantage, one of which is the need to do tuning every change of parameters of the system being modelled.

PID tuning can be done using a variety of methods. The most widely used tuning method is using the Ziegler-Nichols method, the Cohen-Coon method, and the direct synthesis method. Direct synthesis method has better performance than the other two tuning methods [12]. But the direct synthesis method is quite difficult to apply in hardware, so in this paper still uses the Ziegler-Nichols method.

The electromagnetic force suspension system is made with the Maglev effect approach. The Maglev effect is an electromagnetic force that causes objects to float because of the levitator force. The levitator is the source of the electromagnetic force. The free block diagram of maglev can be seen in Figure 5.

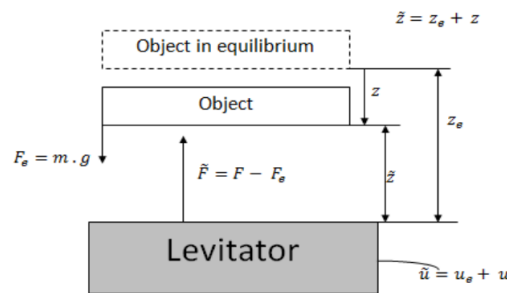


Figure 5. Free block Diagram maglev system.

Preliminary studies of the maglev system with the PID controller produce the specified gap can be achieved immediately even though the maglev system is disturbed by increasing the mass of the raised object [13]. The levitator force that is generated on the Maglev system has two characters, namely attractive and repulsive. Both levitator force characters do have their own advantages and disadvantages, Both levitator style characters do have their own strengths and weaknesses, but if the system wants a fast response then a repulsive force can be a good choice [14].

Maglev system consists of permanent magnets and electromagnets. The electromagnet is a levitator and permanent magnet as a supporting force. The force produced by a permanent magnet can be written with:

$$F_{PM} = BH \times Volume \quad (6)$$

where F_{PM} is the force of the permanent magnet, BH is a magnetic field produced from various types of material from magnets. The permanent material used is neodymium ($Nd_2Fe_{14}B$). The material is able to produce $300kJm^{-3}$.

The electromagnetic force is affected by the magnetic field. Large magnetic fields can be written with Ampere's law approach, where the magnetic field is:

$$B_{EM} = \mu_0 i_0 n \quad (7)$$

where B_{EM} is a large magnetic field, μ_0 is the permeability of air, i_0 is the current through copper wire and n is the number of turns in units of length. With Lorentz's law, equation (7) is processed to become an electromagnetic force into:

$$\vec{F}_{EM} = q\vec{v} \times \vec{B} \quad (8)$$

q is a positive charge and \vec{v} is the vector value of speed. The direction of the force in equation (8) can be obtained by the right-hand rule, so the equation of force becomes:

$$\vec{F}_{ME} = \vec{I}L \times \vec{B} \quad (9)$$

Where \vec{I} is the current passing through the length of the wire from L . The results of this equation are then made into a block diagram from the suspension system. Figure 6 can be seen a block diagram of the suspension system. Whereas in table 1 are the parameters of modelling a quarter of a car.

Table 1. The parameters of the quarter car suspension modelling

Parameter	Value	Description
K_1	25 kN/m	Spring stiffness
K_2	220 kN/m	Tire Stiffness
M_1	375 kg	$\frac{1}{4}$ vehicle mass
M_2	25 kg	Unsprung mass
b_1	1000 Ns/M	Damping passive suspension
b_2	10 kNs/M	Tire passive damping

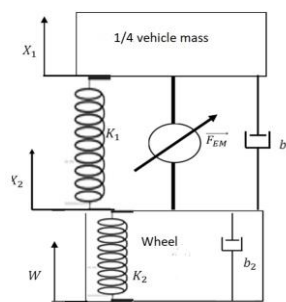


Figure 6. Block diagram of quarter of a vehicle.

One disadvantage of using electromagnets is that a large amount of power is needed. Large power can overload the vehicle engine performance. The hybrid suspension system can be used as a solution [15]. Future research will add air suspension to the active suspension system with electromagnets.

5. Result and Discussion

The first modelling is to observe how much vibration occurs in the vehicle without interference and active control. This modelling needs to be done to determine the response of the suspension system from the force generated from the vehicle itself. The results of modelling and simulation can be seen in Figure 7. The results shown in Figure 7 show that vehicles naturally have vibrations caused by dynamic motion. But the vibration produced is very small, the largest amplitude only reaches 0.0605 mm, this is not felt in driving. The frequency that occurs is also quite small around 1.21 Hz. These frequencies can cause passengers to experience motion sickness.

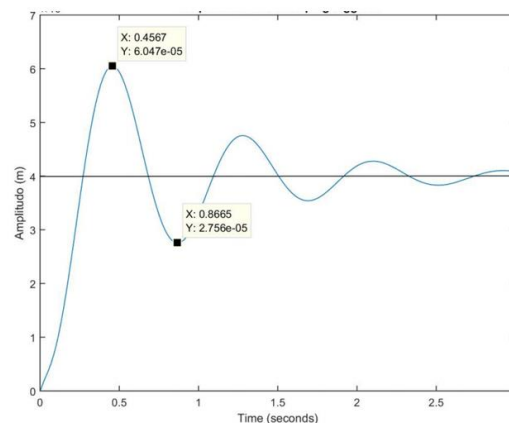


Figure 7. Vehicle response without disturbance

The second test is to see how the response of the suspension system that gets disturbance. Disturbances used are speed limiting devices adjusted to the Minister of Transportation regulation No. 31/1994 Article 5. The article reads: "Vehicle speed limit must be made with a maximum height of 12 cm, a minimum width of 15 cm and a sloping side with a maximum slope of 15° . Disturbances received by the suspension system result in changes in position. Changes in position increased from 0.0605 mm to 109.8 mm. The resulting frequency also experienced a slight change that is to 1.23 Hz. Also in 3 seconds, the suspension system has not been able to return to the reference position (steady-state). The results can be seen in Figure 8.

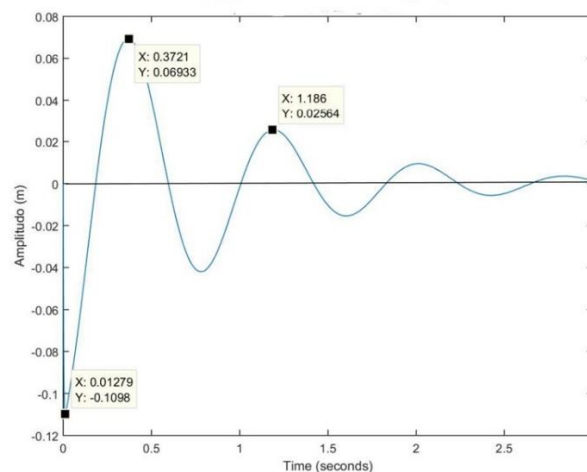


Figure 8. Vehicle response with disturbance.

In the third test is to add active control to the suspension system. The controller used is the PID controller, this is because it is easily applied to hardware. The tuning process uses the Ziegler-Nichols method which then continues to improve the response results. The results of testing added with active control are able to produce a much better response. The change in the position shown from the amplitude is only 18 mm adrift with a suspension system without active control. However, the response time required for the suspension system to return to its original position is 0.8 seconds. The results of this response are much faster than the suspension system without active control, this makes the handling of the active suspension system better. The initial frequency produced is around 4.5 Hz, so the suspension is not at the motion sickness frequency. The results of the suspension response with active control can be seen in Figure 9.

Frequency becomes an interesting problem to be discussed next. High frequency can make passengers uncomfortable when driving long distances. Frequency and amplitude can be removed if the suspension system and the vehicle are not directly connected directly or by using the maglev system.

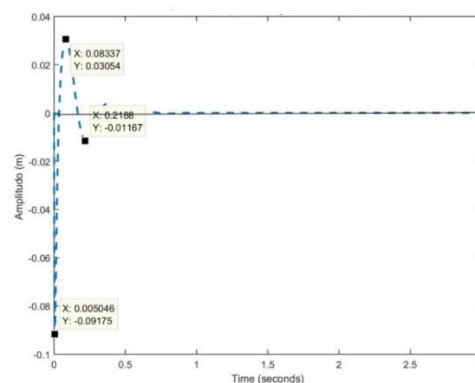


Figure 9. Suspension response with disturbance and active control.

6. Conclusions

The results of the suspension system without disturbance still slightly produces vibrations that make changes in the position of the vehicle. The highest change in position is 0.06 mm with an initial frequency of 1.21 Hz. Within 3 seconds, the suspension system has not been able to reach the reference position.

In the second test, the suspension system was given a disturbance in the form of a speed limit with a height of 120 mm. The results of the test obtained changes in the height of the suspension position is 109.8 mm with an initial frequency of 1.23 Hz. For 3 seconds the position of the vehicle is not able to return to its original position.

The third test by adding active control makes the suspension work better. While the frequency rises to 4 Hz. This frequency does not enter the frequency in motion sickness. The position of the vehicle is also very fast to return to the reference position, this makes handling of the vehicle better.

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