Study & Analysis on
Regenerative Suspension as part of Hybrid Vehicle System

by

Edwin Cheng Eu Winn

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

Approved by,

____
(Dr. Setyamartana Parman)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

April 2009

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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EDWIN CHENG EU WINN

ABSTRACT

In general, this paper is related one of the working principles of hybrid vehicle systems. The development of hybrid vehicles can be assumed to be one of the most important advances in the automotive world today. It has been spurred on by a pressing requirement for the reduction in the environmental impact of land transport, especially regarding urban transport. Apart from all those main advantages of hybrid systems as listed in the project background section, there is also another potential way of recovering energy that would otherwise be lost while driving. Energy can also be recovered from the shock absorbers in a car suspension system itself. It is a process of recovering energy from damped, vibrating suspension system of a car. Environmental and energy issues have been the driving force to increase the quality of vehicle systems to preserve the environment and to further increase the efficiency of energy usage. The objective of the author's project is to perform a study and analysis on regenerative suspension systems utilizing magnetic shock absorbers to harness those otherwise lost energy in a conventional vehicle suspension system. Firstly, the author looks into general information regarding regenerative suspensions. The author then focused more on the regenerative electromagnetic suspension system. In the second semester of this 2-semester project, the author compiled all the CAD drawings that have been modeled. The author initiated the parameters definition process to determine those needed important data of the system. After the author managed to determine all related parameters, the author performed simulations using the ADAMS/Car software to analyze the amount of vertical movements that a car's suspension generates during different driving conditions. The author then proposed those equations that are being used to estimate the amount of regenerative energy that can be saved from those vertical movements as analyzed in ADAMS/Car.

ACKNOWLEDGEMENT

The author is pleased to have finally completed his Final Year Project on a Study and Analysis on Regenerative Suspension as part of Hybrid Vehicle System, after so much hard work and commitments thrown to make it a reality with the time sacrificed for it. The author’s supervisor, Dr. Setyamartana Parman has been very helpful throughout the process of discussion, ideas, opinions and guidance for this project. His useful advice and ideas was a great aid in minimizing and correcting mistakes made during the period. The author is delighted to have him as his supervisor for this project.

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Reference and consultations made are not restricted to the supervisor only. Some of the lecturers from Mechanical Department are also involved in this project as acting coordinators. Dr. Puteri and Professor Vijay have been helpful in coordinating the whole Final Year Project thoroughly. Million thanks to those who assisted in one way or another to make this project possible.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND STUDY

The development of hybrid vehicles can be assumed to be one of the most important advances in the automotive world today. It has been spurred on by a pressing requirement for the reduction in the environmental impact of land transport, especially regarding urban transport. The term “hybrid” means the bringing together of two types of vehicle propulsion system, normally mechanical and electrical, drawing the best aspects and characteristics of each, to produce a vehicle far more efficient than the conventional ones. (Jefferson & Barnard, 2002) [8].

1.1.1 Why Hybrid?

Part of the hybrid propulsion system provides a means of improving fuel efficiency and a reduction of the emissions for most forms of land transport. Indirectly, such improvements will also benefit a number of different issues, as shown in the following:

- A reduction in the cost of transportation
- A reduction in the rate of fossil fuels depletion
- A reduction in the level of atmospheric pollutants, especially the urban areas
- A reduction of greenhouse gases

Other than that, there are actually further additional benefits depending on its hybrid arrangement which includes quieter operation, the ability to function in a zero emission mode for short distances and even operate on a stepless transmission. [8]

1.1.2 Concept of Hybrid Vehicle

The definition of hybrid vehicle can be defined as a vehicle having two power sources. Normally, the condition of layout of hybrid vehicles will have one of its power source derived from fuel power, while the other power source relies on stored energy which can be used for extra power at various stages during a journey when needed. When the stored energy needs to be replenished or refilled, it can be done by using the fuelled power source or by recovering energy that would be lost during braking. Generally, by using a hybrid system, a smaller main engine can be used compared to the engine size that is normally being used in the corresponding conventional vehicle. This is due to the fact that only a fraction of the maximum engine power is normally used for the greater part of any journey for a particular vehicle. The short bursts of high power that is needed for acceleration and hill climbing purposes can be provided from the stored energy. Besides, since the energy storage capacity for a hybrid car is limited, it enables energy that would normally be lost in braking in a conventional vehicle to be garnered and stored so that it can be used later on.

The advantages or the benefits of the arrangement of hybrid propulsion system can be appreciated by considering the behavior of such a system during a simple, short start/stop journey cycle. Figure 1.1.2 (a) below depicts the speed history.

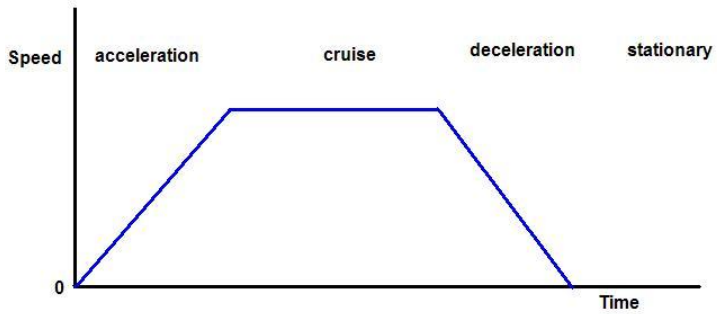


Figure 1.1.2 (a): The ideal speed profile for a stop/start cycle on a light rail vehicle

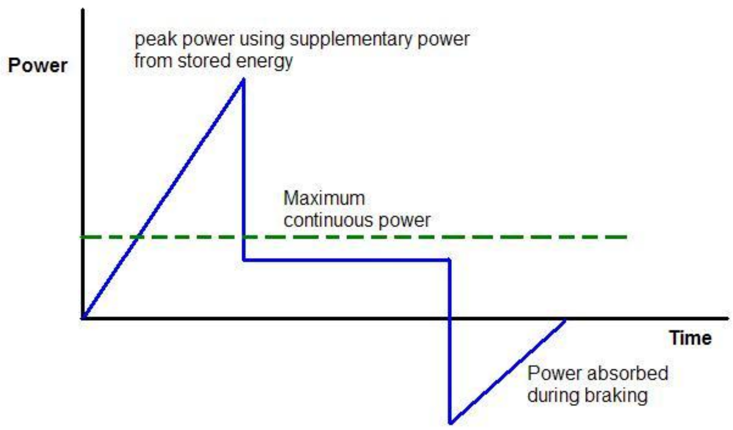


Figure 1.1.2 (b): The corresponding theoretical power demand by the propulsion system

As we can see in figure 1.1.2 (b), in a particular journey for a normal vehicle, only a small fraction of the maximum engine power will be used for the greater part of the journey. In other words, we can observe that high power in only used for a very small part of the journey. Therefore, for a hybrid vehicle propulsion system, the additional power needed for acceleration is normally taken from the stored energy device for large energy storage hybrids. As in contrast for mild hybrid vehicle, the primary motor is sized so that its power is at least adequate for cruise.

Figure 1.1.2 (c) shows the common behavior of a hybrid arrangement during the acceleration phase. Basically the smaller engine has to work at a more constant power setting using a higher percentage of its maximum capable power than the large engine in a normal vehicle. Compared with an internal combustion engine, this increases it efficiency tremendously. Spark-ignition engines have poor part-load efficiency. [8]

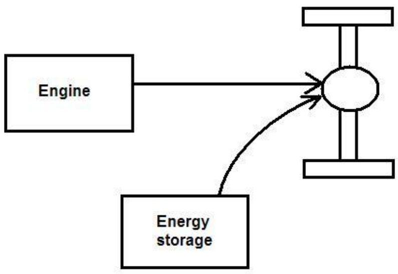


Figure 1.1.2 (c): Hybrid arrangement during the acceleration phase

As for during the cruise phase, some spare power capacity from the main power source, normally a fuelled power source will be used to top up the energy in the storage device as a form of “recharging” it. Figure 1.1.2 (d) shows this particular phenomenon. [8]

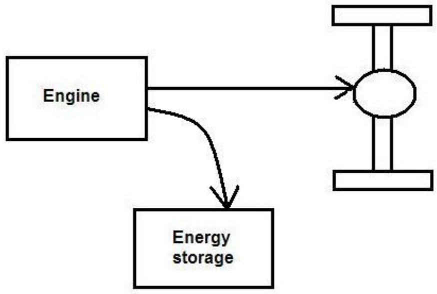


Figure 1.1.2 (d): Hybrid arrangement during the cruising phase

Apart from this, as can be seen from figure 1.1.2 (b), when the vehicle is trying to stop, in other words, during deceleration, the power requirement shows in the negative region. This shows that energy has to be absorbed by the braking system. As one of the advantages in a hybrid vehicle propulsion system, instead of just dissipating this energy as heat in the braking system, the energy storage device can be used to absorb and recycle it. This further increases the fuel economy for the vehicle. For example, in a hybrid system where a battery is being used as the storage device, the wheels of the vehicle are mechanically connected with an electrical generator which actually supplies current to recharge the storage unit and at the same time, provides a braking resistance load to the wheels in order to perform the braking mechanism. This is being shown schematically in figure 1.1.2 (e).

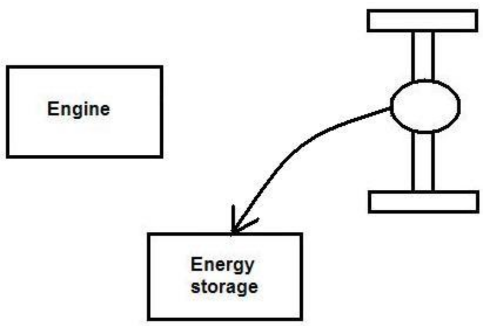


Figure 1.1.2 (e): Hybrid arrangement during the braking phase

Apart from what is being discussed here, there are lots more advantages and benefits of the hybrid propulsion arrangement. For instance, there is a possibility of using the stored energy to rapidly restart the main engine which can therefore be switched off during periods of inactivity; in traffic jams or during long traffic stops.

As an overview, the three main advantages of a hybrid system are:

- Recovery of energy that is normally lost during braking
- A reduction in size of the primary engine power source
- Optimization of the primary power source where it operates at a more constant load and thus more efficient

1.1.3 Regenerative Energy

Apart from all those main advantages of hybrid systems as listed in the previous section, there is also another potential way of recovering energy that would otherwise be lost while driving. Energy can also be recovered from the shock absorbers in a car suspension system itself. It is a process of recovering energy from damped, vibrating suspension system of a car. This emerged due to the need of the automotive world today for continuous improvement of vehicle’s energy efficiency, and the potential benefits from the development of regenerative vehicle suspension systems.

A vehicle’s level of energy efficiency can be improved by either reducing the amount of energy required to propel the vehicle or by efficiently producing the energy for propulsion. However, the energy required to propel a vehicle is governed by many factors, including drag resistance and rolling resistance to name a few. To some extend, these resistance can be minimized or reduced especially with new ideas and technology today. Nevertheless, it is not possible to eliminate energy loss entirely by these methods. Therefore, a method of improving energy efficiency is through regeneration or recovery of the energy that is ordinarily dissipated to the external environment.

In a conventional vehicle suspension system, it consists of passive elements which are the viscous damper and spring. The damper's function is to limit the vertical wheel motion caused by a vehicle when moving across uneven road surfaces. However, the damper's working nature results in energy being wasted or lost. More specifically, vibrational energy is being converted into heat whenever there's movement of the damping fluid in a conventional hydraulic vehicle damper. The heat energy will then be dissipated to the environment through cooling as the vehicle moves, thus wasting energy. However, in a regenerative vehicle suspension, the conventional damper is replaced by a regenerative damper where it will recover those lost energy.

1.2 PROBLEM STATEMENT

In the automotive industry, there is always room for improvement. Environmental and energy issues have been the driving force to increase the quality of vehicle systems to preserve the environment and to further increase the efficiency of energy usage. One way of achieving this is through regenerative devices and components to restore energy that would be lost in a conventional vehicle.

1.3 OBJECTIVE AND SCOPE OF STUDY

The objective of the author's project is to perform a study and analysis on regenerative suspension systems utilizing magnetic shock absorbers to harness those otherwise lost energy in a conventional vehicle suspension system.

CHAPTER 2

LITERATURE REVIEW

2.1 OVERVIEW

This literature review presents studies and investigations carried out by other researchers related to this field of regenerative dampers and suspensions.

The study on the potential benefits of an energy-regenerative active suspension for vehicles had been carried out by *Xuechun Zheng and Fan Yu* [1] from Shanghai Jiao Tong University. They [1] mentioned that active suspensions are still not widely used in vehicles today due to their high energy consumption.

Therefore, they [1] investigated the energy consumption of a passive suspension via damper and the energy demand for an LQG optimal vehicle active suspension initially. Then, they [1] discussed the feasibility of the energy regenerative approach. This is then followed by a proposal of an electrical active suspension configuration along with descriptions of its working principle and structure.

Ebrahimi B., Behrad Khamesee M. and M. Farid Golnaraghi [2] did a study on the development and modeling of a novel electromagnetic damper. This regenerative damper developed by them [2] is based on the concept of a tubular, linear, brushless DC motor and can be used in passive, semi-active and active operating modes.

R. B. Goldner and P. Zerigian [3] did a preliminary study of energy recovery in vehicles using regenerative magnetic shock absorbers. They [3] presented results of their [3] study aimed at determining the effectiveness of efficiently transforming that energy into electrical power by using optimally designed electromagnetic shock absorbers. They [3] built a model and carried out a couple of experiments to validate their findings.

A. Gupta, J. A. Jendrzejczyk and T. M. Mulcahy [4] developed and fabricated two configurations of regenerative electromagnetic shock absorbers, a linear device and a rotary device. They [4] described the performance of their prototypes through a laboratory test stand and in a small all-terrain vehicle. David A. Oxenrider had a similar idea in developing an electromagnetic linear generator and shock absorber. What has been designed by him is similar to what Goldner and Zerigian did in their [3] studies. *Fodor and Redfield* [5] also described regenerative damping schemes using theoretical analysis.

Great importance need to be given to a particular Degree of Doctor of Philosophy Thesis by *Kynan E. Graves* [6] for his detailed work on electromagnetic energy regenerative vibration damping.

Professor Amarnath, Kaushik J and Ankit Mehta [7] also managed to design a type of regenerative shock absorber which consists of a series of coaxial cylinders mounted on a lead screw.

2.2 ENERGY REGENERATIVE ACTIVE SUSPENSION

Apart from just effectively isolating the vibrational excitation from uneven road surfaces, the other objective of the research done by *Xuechun Zheng and Fan Yu* [1] is also to restore the vibration energy as much as possible. They [1] carried out the electro-chemical regenerative approach. As shown figure 2.1, it can convert most vibration energy into electrical energy through the rotation of a motor and store them in an accumulator or a capacitor.

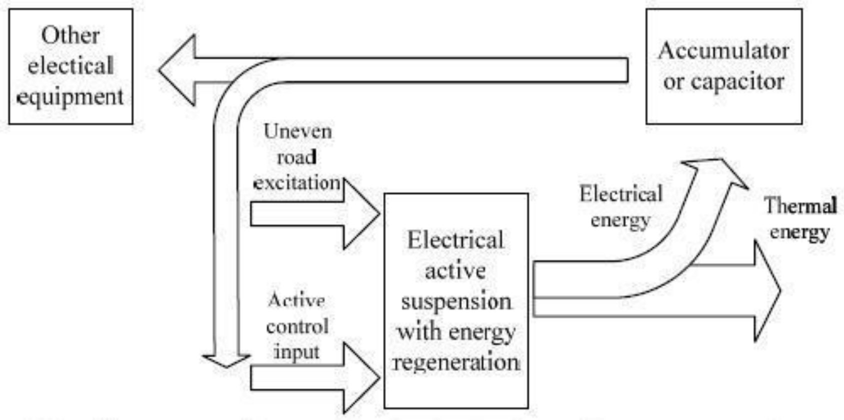


Figure 2.2.1: Energy flow of electrical active suspension

The structural design of the electrical active suspension is introduced in a quarter vehicle model by them [1]. As shown in figure 2.2, it contains a body mass, a wheel mass, a suspension spring, an electrical motor actuator, a drive and energy storage circuit, a microprocessor, a suspension working deflection sensor and so on. The electrical energy-regenerative active suspension designed by them [1] can therefore recycle the vibration energy caused by uneven road surface excitement and thus reduce suspension energy dissipation.

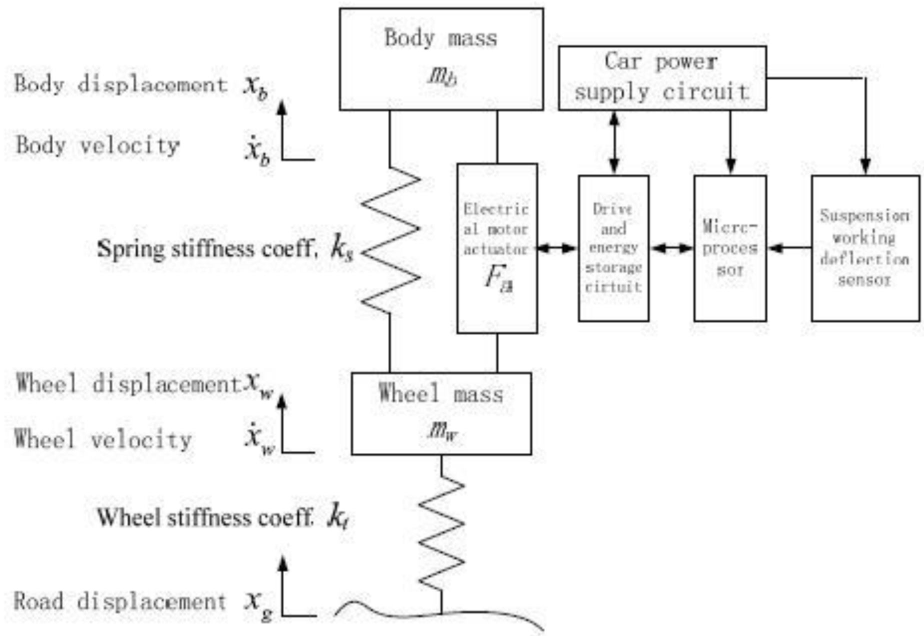


Figure 2.2.2: Electrical active suspension structure

The proposed electromagnetic damper by *Ebrahimi B., Behrad Khamesee M. and M. Farid Golnaraghi* has energy harvesting capability as well. Generally, their [2] proposed electromagnetic damper works as a generator converting kinetic energy of vibration into electrical energy in the passive or semi-active mode. In the active mode, its coils are energized in order for the electromagnetic damper to work as an actuator. Furthermore, they [2] also developed a prototype and experiments were done with it to verify the accuracy of the numerical model. Figure 2.3 below depicts the configuration of the damper proposed by them [2].

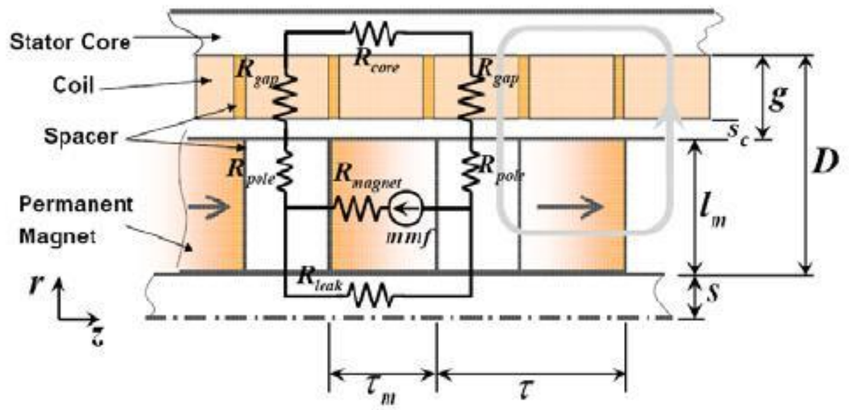
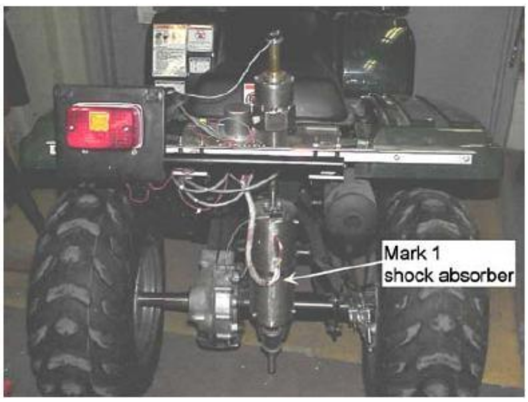


Figure 2.2.3: Configuration of the damper with equivalent magnetic circuit

2.3 ELECTROMAGNETIC REGENERATIVE DAMPER

A. Gupta, J. A. Jendrzejczyk and T. M. Mulcahy [4] designed two types of electromagnetic regenerative shocks, known as Mark 1 and Mark 2. These can be shown in the figures below.



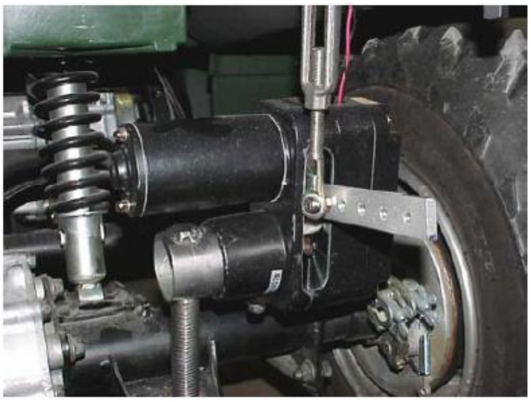


Figure 2.3.1: Mark 1 (left) and Mark 2 (right) shock absorber mounted on test vehicle

Mark 1 consists of a few very powerful permanent magnets mounted to the outer sleeve and a moving coil assembly mounted to a sliding armature. The coils that are moving in the magnetic field generate electrical power. Mark 2 on the other hand consists of a small DC motor coupled to a lever arm by a system of gears. They [4] used a small all terrain vehicle to perform their experiments and tests. Apart from this, Mark 1 and Mark 2 also were being used for testing in an electrodynamic shaker. This is shown in figure 2.3.2.

Figure 2.3.2: Mark 1 shock tested on electrodynamic shaker

Significant amount of power was generated from these 2 dampers designed by them [4]. Apart from this study, *Fodor and Redfield* [5] also introduced a device, known as the Variable Linear Transmission for regenerative damping to accomplish energy regeneration. They [5] stated that the primary action of regenerative damping is to transfer vibration energy to an energy storing device as efficiently as possible while maintaining acceptable vibration control. Their research put a lot of importance on impedance matching between the source and the storage device to maximize the regeneration efficiency. This actually refers to the ratio of "efforts" and "flows" in an energy transfer system. "Efforts" refer to the force and voltage in mechanical and electrical systems respectively. "Flows" refer to the velocity and current in mechanical and electrical systems respectively. They [5] described how energy storage devices has a "barrier potential" which need to be overcome before storage of energy can begin.

The device introduced by them [5] used a mechanical method of energy regeneration. Their [5] device uses a mechanical lever and movable fulcrum mechanism. This can be shown in figure 2.3.3.

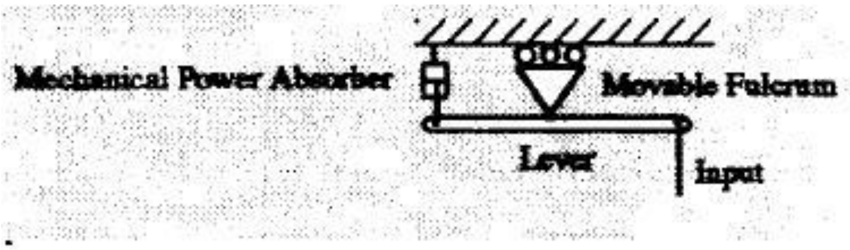


Figure 2.3.3: Variable linear transmission

However, in conclusion to their [5] study performed, they [5] stated that their results show that the device is not that feasible as a regenerative damper due to some limitations. They suggested that a more advanced fulcrum control strategy was needed or the reduction of the fulcrum motion from two to one degree of freedom was needed to improve its feasibility.

Professor Amarnath, Kaushik J and Ankit Mehta [7] did a study on Regenerative Shock Absorber from December 2004 to January 2005. Their design of the regenerative shock absorber, the RSA, consists of a series of coaxial cylinders mounted on a lead screw. Between the outermost set of cylinders are two sets of spiro-helical springs which coil and uncoil alternately as the setup slides up and down along the lead screw and thus rotate the outermost cylinders.

The outermost cylinders have gears mounted on them which are further engaged to gears on motors. These motors now function as dynamos converting the mechanical energy of the spinning cylinders to electrical energy that can be stored in a battery. [7]

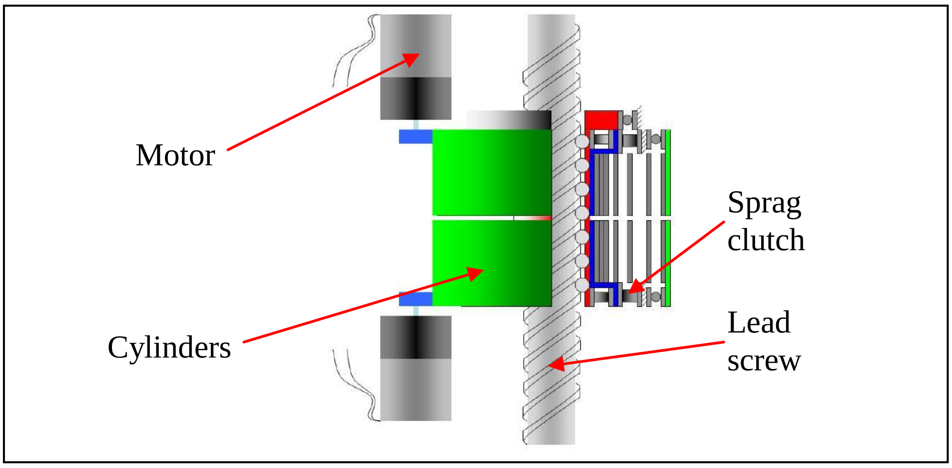


Figure 2.3.4: Sectional view of the regenerative shock absorber designed by Professor Amarnath

Figure 2.3.4 depicts the sectional view of the regenerative shock absorber designed by Professor Amarnath. The working principle of the RSA can be understood with the following example. Consider a shock load being transmitted to the lead screw of the RSA. This will then move the set up of the RSA downwards along the lead screw. The transmitted shock will then be converted into rotary motion of the inner cylinder resulting in the coiling of one of those springs; let's say the upper spring for instance. The corresponding outer sprag clutch is being jammed, preventing the rotation of the outer cylinder, thus keeping the spring coiled up. The lower spring is unaffected as the inner sprag is jammed. Now, the set up has to recoil and regain its normal position. As the set up moves up, the outer sprag clutch on the top is free while the inner one is jammed. Now the outer cylinder is free to rotate and corresponding spring uncoils. Meanwhile, the inner sprag clutch on the lower side is free while the outer one is jammed resulting in winding of the lower spring. This spring will uncoil itself when the set up moves down again after another shock. The cycle continues.

Figure 2.3.5: Prototype of the RSA mounted on a bike

CHAPTER 3

METHODOLOGY

3.1 FLOW CHART

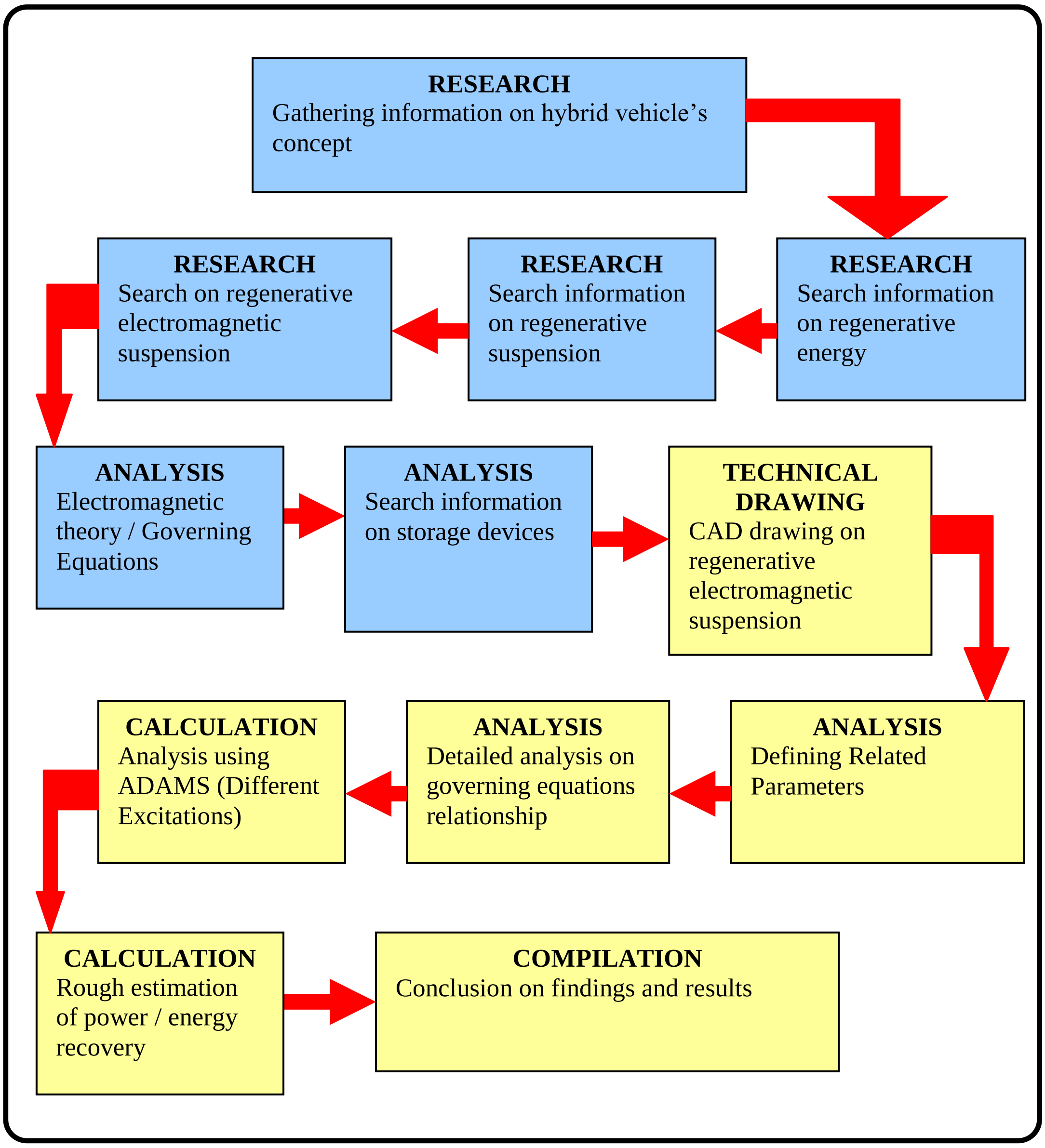


Figure 3.1.1: General flow chart of activities

Figure 3.1.1 depicts the general idea and activities that the author will carry out in order to achieve the objectives of this project. Firstly, the author researched and gathered information relating to hybrid vehicle's concept. The author then looked into the advantages and disadvantages of various types of hybrid vehicle drivetrains. This is done to get an overall idea on the working principle of hybrid vehicles along with its different features and components. One of the most important parts of the hybrid vehicle working principle is to strive for energy efficiency. The author then researched and gathered more information, journals and studies made regarding regenerative energy on related vehicle systems.

In order to achieve the objective of this project, the author researched information on various regenerative suspension systems. The author then focused on a particular type of regenerative suspension system which is the regenerative electromagnetic suspension system. The author then gathered information relating to electromagnetic theory and governing equations along with calculations that are needed in analyzing the regenerative electromagnetic suspension system. Apart from this, the author also searched for information regarding the various types of storage devices that can be used along with its pros and cons and practicality of those storage devices. A CATIA (CAD) drawing of the general idea of the regenerative electromagnetic suspension system is then prepared for better understanding and illustration purposes.

At the second half of the Final Year Project, the author defined the important parameters that were needed to perform those specified calculations. These parameters range from the magnet strength to the important dimensions of the suspension system. The author then uses the ADAMS/Car software to perform analysis on the general amount of excitations that a conventional suspension system of a vehicle will receive in different road conditions. Upon completing the analysis, the author then performed rough calculations using those equations to estimate the rough value of the amount of power or energy that can be harnessed or recovered from the excitation of the electromagnetic suspension system.

3.2 PROJECT GANTT CHART

Table 3.2a: Project Gantt chart for Semester 1

No.	ACTIVITIES	SEMESTER 1 (Week)																		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	Submission of Project Topic	■	■									M								
2	Preliminary Research Work on Different Hybrid Systems		■	■	■							i								
3	Submission of Preliminary Report				■							d								
4	Continue research on different hybrid systems				■	■	■													
5	Advantages & disadvantages of each hybrid system				■	■	■	■	■	■		-								
6	Submission of Progress Report								■			S								
7	Seminar								■			e								
8	Search information regarding regenerative energy								■	■	■	m	■	■						
9	Search information regarding regenerative suspension system										■		■	■	■					
10	Findings on regenerative electromagnetic suspension system											B	■	■	■	■	■	■	■	■
11	Findings on electromagnetic theory / governing equations											r			■	■	■	■	■	■
12	Information on different types of storage devices											e				■	■	■	■	
13	CATIA drawing on basic electromagnetic suspension system											a							■	
14	Submission of Interim Report											k							■	
15	Oral Presentation																			■

Table 3.2b: Project Gantt chart for Semester 2 (Final semester)

No.	ACTIVITIES	SEMESTER 2 (Week)													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Project work continue														
2	Defining Parameters										M				
3	Submission of Progress Report 1										i				
4	Detailed analysis on governing electromagnetic equations										d				
5	Analysis using ADAMS (excitations in different road conditions)										- S				
6	Rough estimation on power / energy recovery										e				
7	Submission of Progress Report 2										m				
8	Seminar														
9	Poster submission										B				
10	Compilation of findings and results										r e				
11	Submission of Dissertation (soft bound)										a				
12	Oral Presentation										k				
13	Submission of Project Dissertation (Hard bound)														

CHAPTER 4

RESULTS AND DISCUSSION

4.1 BASIC STRUCTURE OF DEVICE

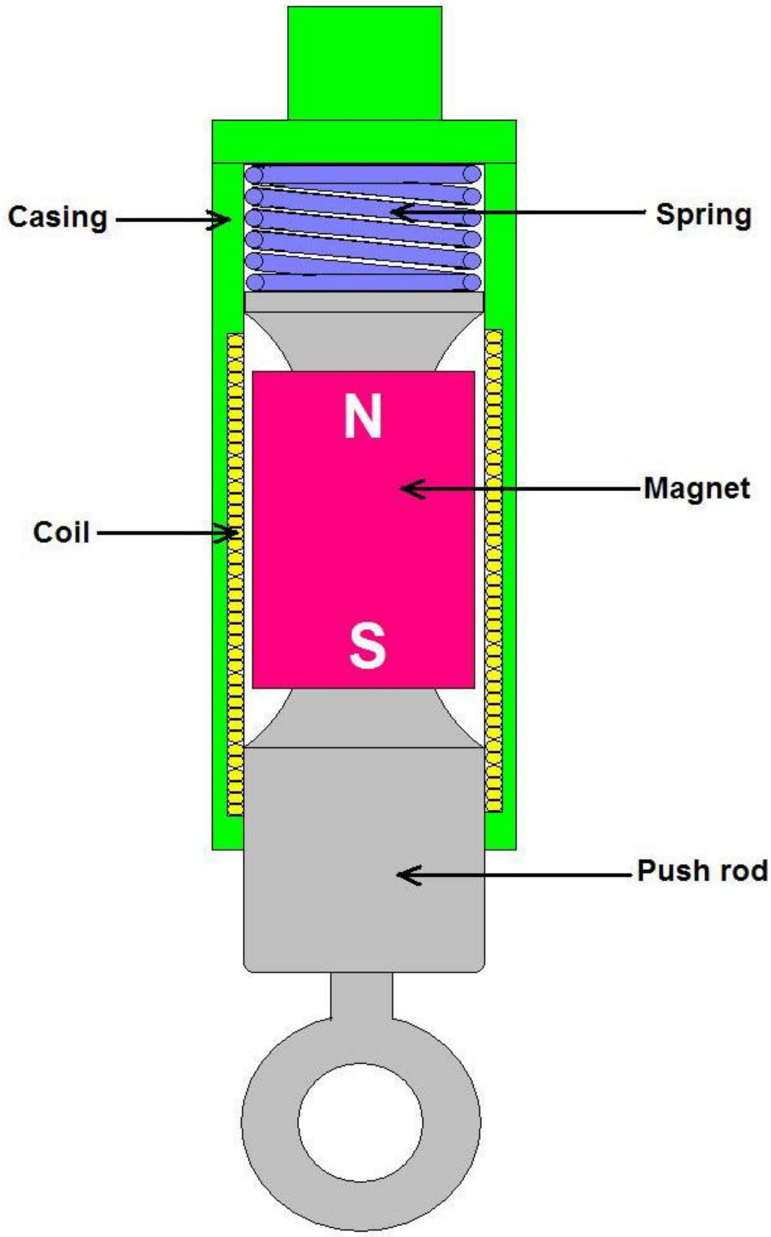


Figure 4.1.1: Basic structure of the electromagnetic shock absorber system

Figure 4.1.1 depicts the basic and general structure of the electromagnetic shock absorber system along with its components. Basically, the permanent magnet will move vertically upwards or downwards along the enclosed casing. The enclosed casing also consists of the coils which are connected to the electrical energy storage device or directly supplying electrical energy to certain vehicle electrical components. The spring supports the permanent magnet and its push rod that will be connected to vehicle wheel components.

4.2 CAD DRAWING

The author prepared a model of the regenerative shock absorber by using an engineering modeling software, CATIA. This is to depict the system in a much clearer way for understanding purposes. Basically, the model shows the magnet to be enclosed in a closely-spaced coil, all being assembled together to form the regenerative shock absorber system.

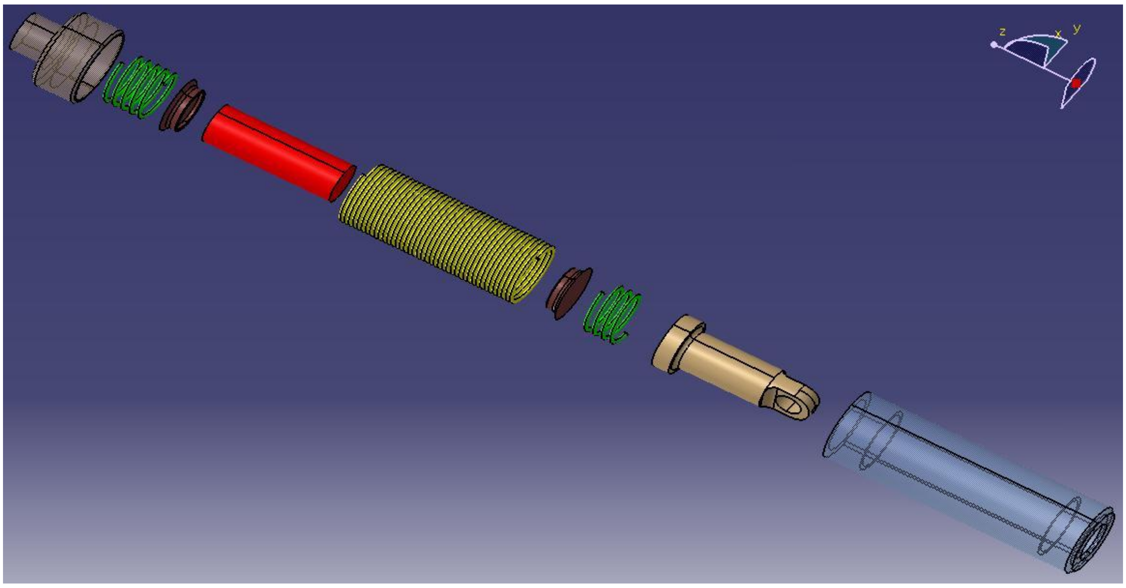


Figure 4.2.1: Exploded view of the regenerative system

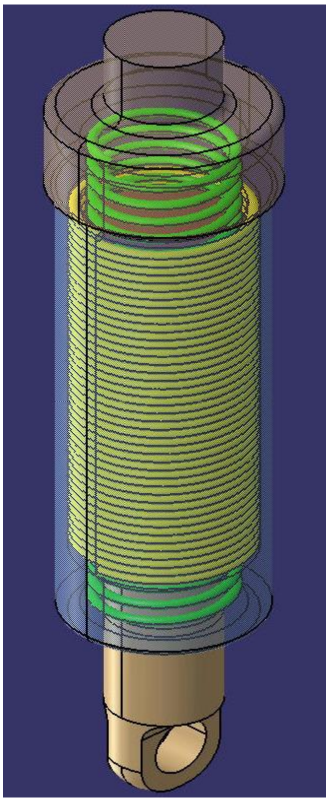


Figure 4.2.2: Assembled isometric view of the regenerative system

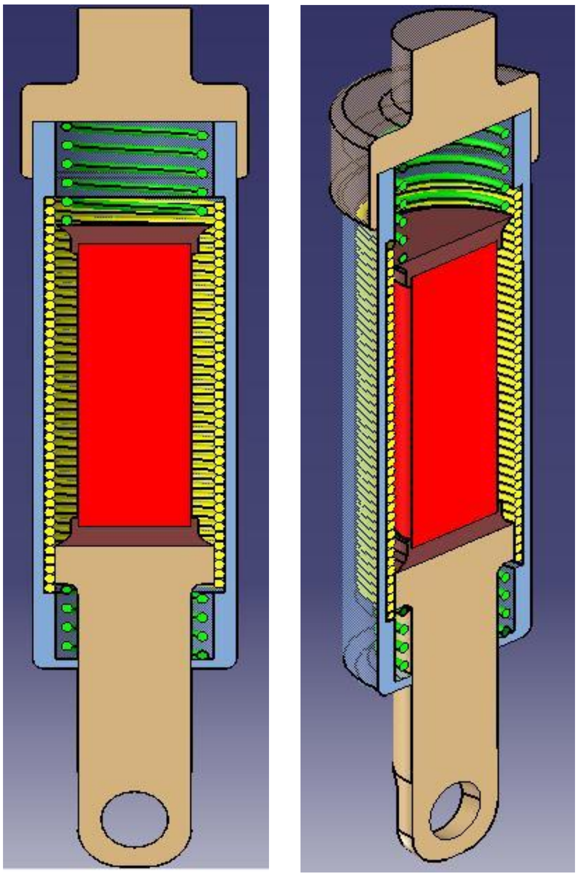


Figure 4.2.3: 2-dimensional (left) and 3-dimensional cut-away view

From figure 4.2.3, the working principle of the regenerative shock absorber system can be depicted easily. The red-coloured part in the figure is the cylindrical magnet that will move axially along the inside of the closely-spaced coil, which is yellow in colour. The springs, which are green in colour are being placed above and below the magnet just to make sure the magnet moves back to the same place after it moves axially due to bumps or unevenness of the road profile.

4.3 ELECTROMAGNETIC EQUATIONS

Basically, to understand and know how does the kinetic energy generated when displacements are induced in a vehicle suspension system can be converted into electrical energy for storage, one need to understand the electromagnetic theory in detailed. Figure 4.3.1 shows the basic energy transfer modal of a generalized electromagnetic machine.

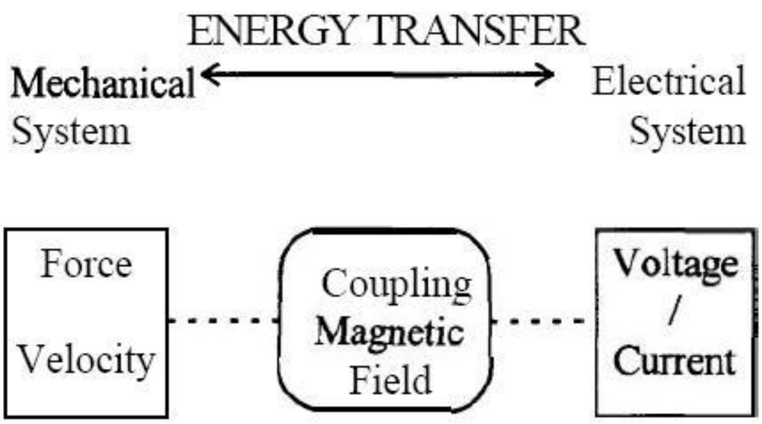


Figure 4.3.1: Representation of electromechanical energy conversion [6]

It is shown that energy transfer takes place in the device through a magnetic field that is coupled between the mechanical and electrical system. The damping response is established by the force-velocity characteristic of the device. As for the energy regeneration part of the device, it is governed by the voltage-current relationship from the electrical device.

Figure 4.3.2 shows an illustration of the schematic diagram of a regenerative electromagnetic shock absorber.

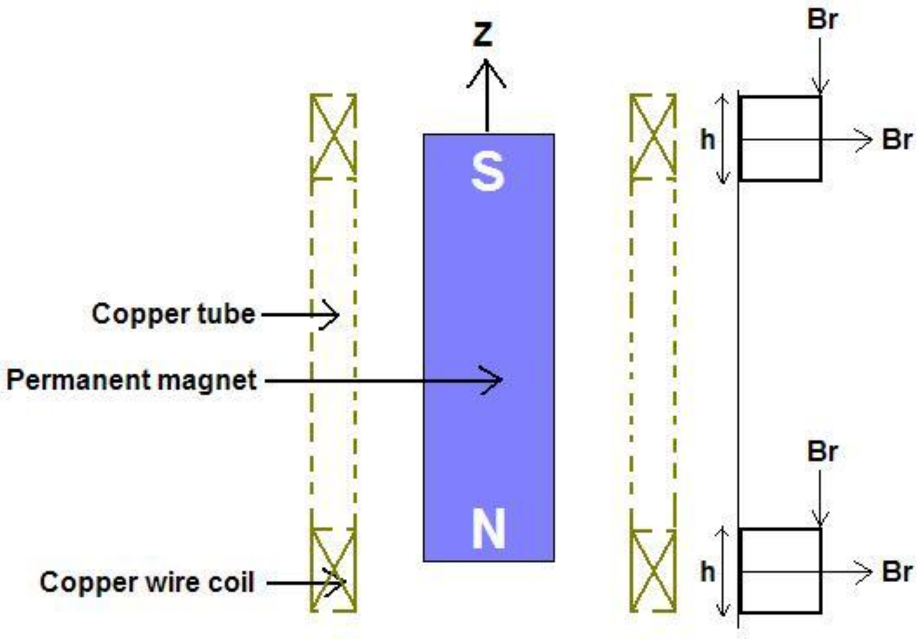


Figure 4.3.2: Schematic diagram of permanent magnet moving in a copper wire coil / copper tube

To simplify the calculations, consider a magnet rod is being dropped through a copper wire coil or through a relatively long copper tube. The Lorentz electric field in the copper wire coil or in the equivalent region of the copper tube with a relative velocity v_z in a radial magnetic field of flux density, B_r can be represented by [3]:

$$E_{Lorentz} = E_{\phi} = v_z B_r$$

The corresponding Eddy current density can be represented in the following equation [3]:

$$J_{\phi} = \sigma_{Cu} E_{\phi}$$

The differential eddy current passing through a differential cross-section area, dA is shown as [3]:

$$dI = J_{\phi} dA$$

From here, the differential back or damping force on the differential volume d(vol) can be shown as [3]:

$$
\begin{aligned}
\left|dF_{back}\right| = \left|dF_{damping}\right| &= dF_d \\
&= \left(J_\phi\right)\left(B_r\right)d(volume_{coil}) \\
&= \left(\sigma_{Cu}\right)\left(B_r^2\right)d(volume_{coil})
\end{aligned}
$$

When this is being integrated, the damping force becomes the following [3]:

$$F_d \approx \left\{\sigma_{Cu} \times B_r^2 \times Volume_{coil}\right\} \times v_z \equiv \gamma \times v_z$$

The damping force acts like a repulsive force which counters the movements of the magnet. Every electromagnetic device or system will encounter a force similar to this. Because of this repulsive force, it is able to function as a damper system for the electromagnetic suspension.

From here, we have g which is equals to the acceleration due to earth's gravity force [3]:

$$m_{mag}\left(\frac{dv_z}{dt}\right) = m_{mag}g - F_d = mg - \gamma v_z$$

By rewriting this, we will have [3]:

$$\frac{dv_z}{dt} + \left(\frac{\gamma}{m} \equiv \tau^{-1}\right)v_z = g$$

Solving this by using an initial velocity of 0 [3]:

$$v_z = v_{ter\min al} = v_T = g\tau\left(1 - e^{-\frac{t}{\tau}}\right)$$

As for the electromotive force emf, V_e, it can be calculated from the equation as shown below [3]:

$$V_e = \int_{coillength} E_\phi dL_{coil} \approx (B_r) v_z L_{coil}$$

As for the amount of current, the equation that governs it can be written as shown [3]:

$$I \approx \sigma_{Cu} (B_r) v_z A_{wire}$$

As the diagram considered 4 coils, we can therefore write an expression for the maximum power that can be generated for each coil itself. The equation that governs this is as shown [3]:

$$P_{\max} = V_e I \approx (\sigma_{Cu})(v_z^2)(B_r^2)(Volume_{coil})$$

σ_{Cu}	= The electrical conductivity of copper
v_z	= The vertical velocity of the magnet/ suspension at an excitation
B_r	= The strength of the magnet
$Volume_{coil}$	= The volume of the coil with respect to the amount of vertical suspension movement

In order to calculate the volume of the coil, the equation below can be used:

$$Volume_{coil} = L_{coil} A_{wire}$$

Basically, these are among the equations that govern the basis to estimate the amount of power or energy recovery that one might be able to achieve or obtain by replacing the conventional shock absorbers with the optimized magnetic shock absorbers for better efficiency.

4.4 ENERGY STORAGE

There are many forms of energy that can be considered as the final energy type for storage. Electrical energy has a few advantages compared to other forms of energy storage. Firstly, the process of storing electrical energy is a rather straight-forward process compared to other forms of energy. This simplifies matters and will be more practical as well. Other than that, electrical energy is also useful for many subsequent applications, particularly in vehicle applications. Those stored electrical energy can be used directly without the hassle of converting the different types of energy form into electrical energy. Examples include lightings, head lamps and also electric motors [6].

Electrical energy can be stored in devices such as rechargeable batteries, capacitors which are actually relatively practical and efficient energy storage devices. As for an example, ultra-capacitors can be used if there is a need for high power, short-term energy storage. Rechargeable batteries can be used if longer-term energy storage is needed [6].

There are many other types of ways to store energy apart from the electrical form. These include mechanical, chemical and thermal storage as well. Each of these storage methods has its own pros and cons. For chemical energy storage method, one will be able to gain a high energy density storage system. However, the downside of this method of storage is the difficulty that we will face during the conversion between mechanical and chemical energy [6].

Another option that is available is was thermal energy storage. This method of storing energy generally has a lower efficiency compared to other methods. Long term storage for thermal energy storage was also not possible as the storage efficiency is compromised due to energy lost in the form of heat [6].

Other than those mentioned, there is also the possibility of storing energy by using flywheels and mechanical springs. These devices generally have the potential of high storage efficiency. Despite this, these devices are not being considered as there is much complication in incorporating these devices in vehicle systems. In other words, for the usage of flywheels or mechanical springs to be possible, the execution of these types of systems would not be straight forward. Direct method of energy conversion will keep the efficiency relatively high most of the time [6].

4.5 PARAMETERS DEFINITION

The author needs to decide on necessary parameters in order to be able to carry out those calculations efficiently.

4.5.1 Permanent Magnets

Generally, there are three types of magnets found today. There are:

- Permanent Magnets
- Temporary Magnets
- Electromagnets

By and large, we are more familiar with permanent magnets as they can be found almost everywhere easily. They are known as permanent magnets due to the fact that once the magnets are magnetized, they retain a level of magnetism in them. However, different types of permanent magnets will have different properties or characteristics regarding its rate of being demagnetized, how strong they can be as well as their strength properties when contacting higher temperatures.

There are four classes of permanent magnets. They can be categorized as:

- Neodymium Iron Boron (NdFeB)
- Samarium Cobalt (SmCo)
- Alnico
- Cerramic or Ferrite

Neodymium Iron Boron and Samarium Cobalt are generally known as rare-earth magnets. Their compounds come from the Lanthanide series in the Periodic Table. Generally, they are the strongest compared among other permanent magnets. In addition to that, they are also extremely durable as they are not easily demagnetized. The Br of Neodymium magnets are generally more than 11000 Gauss. Therefore, it has a strong holding strength compared to other types of magnets. However, a setback of Neodymium magnets is the fact that they are sensitive towards temperature change. At high temperature, these magnets might lose their magnet properties. Surface protection is also needed for Neodymium magnets. They are somewhat more vulnerable to humid environment compared to other types of magnets. Generally, Neodymium magnets are considered hard and brittle.

Alnico magnets are actually made up of a composite of aluminum, nickel and cobalt. These magnets have good temperature stability. Other than that, Alnico magnets also have good resistance to demagnetization due to shock.

Ceramic or also known as ferrite magnets are generally made from the combination of iron oxide and barium or strontium carbonate. These magnets are desirable due to the fact that the raw materials needed to manufacture ceramic magnets are abundant and readily available.

The second types of magnets are known as temporary magnets. These types of magnets will have the ability to act like a permanent magnet once they are being placed within a strong magnetic field. However, as soon as the magnetic field that they are in disappears, their magnetism ability disappears as well. Common examples would be stationeries like paperclips and household nails.

Oh the other hand, an electromagnet is generally an iron core which is tightly wounded with coils of wire. The iron core will have the ability to act like a magnet with certain strength of magnetism when current is passed through those coils of wire. The strength and polarity of those created magnetic field can be controlled and adjusted by merely changing the magnitude of the current that is flowing through those coils of wire and also the current flowing direction.

We now know that there are many different types of magnets offering various characteristics. The author decides to apply a Neodymium Iron Boron magnet to the regenerative shock absorber system as this type of magnet offers the greatest amount of magnetic strength. As the application of regeneration requires strong magnetic energy, this characteristic offered by the Neodymium Iron Boron magnet overrides the other disadvantages of the magnet.

4.5.2 Dimensions

There are a few parts of the regenerative shock absorber that needs to be determined regarding its dimensions. The following are those critical dimensions that need to be decided in order to perform the energy calculations efficiently:

- Magnet strength
- Magnet diameter and length
- Coil wire diameter and length

Generally, the suspension type of the regenerative shock absorber will resemble a Macpherson Strut type suspension system. Therefore, the author performed analysis and research into common dimensions and sizes of Macpherson Strut type suspensions to decide on the size required in the analysis.

Table 4.5.2.1: Various magnet properties [9]

Material	Br	BH_{max}	T_{coef} of Br	T_{max}
NdFeB	12,800	40	-0.12	150
SmCo	10,500	26	-0.04	300
Alnico	12,500	5.5	-0.02	540
Ceramic or Ferrite	3,900	3.5	-0.2	300

Br : Magnetic flux density in Gauss

BHmax : Overall energy density

Tcoef : Temperature coefficient in Br in terms of percentage per degree centigrade. How magnetic flux changes with temperature)

Tmax : Maximum magnet operation temperature

Based on table 4.5.2.1, we would choose to use NdFeB as our choice of magnet since it has the highest overall energy density, as mentioned before. Although the operating temperature of NdFeB magnet is low, the high energy density of the magnet overrides the importance of its operating temperature. The author stresses that to gain more regenerative energy; a stronger magnet is an advantage.

As for the dimensions of the coil wire, it would first be an estimation just to initiate the calculations. After that, if time permits, optimization of the system will be conducted by changing these variables to suit the purpose of the regenerative system.

4.6 ADAMS SIMULATION

The author utilizes the ADAMS/Car software to perform simulations. ADAMS/Car is an engineering software which is able to perform numerous types of simple and complex iterations in order to simulate various working conditions of the vehicle in reality. In this project, since the objective of performing this simulation is to determine the quantity of spring movements on the car when undergoing various selected road types or profiles, an assembly car model which is already prepared in ADAMS/Car in default is selected. The amount of vertical movements of the springs (or magnet) can be an indication of the amount of energy that is possible to be regenerated. Figure 4.6.1 below depicts the model in ADAMS/Car.

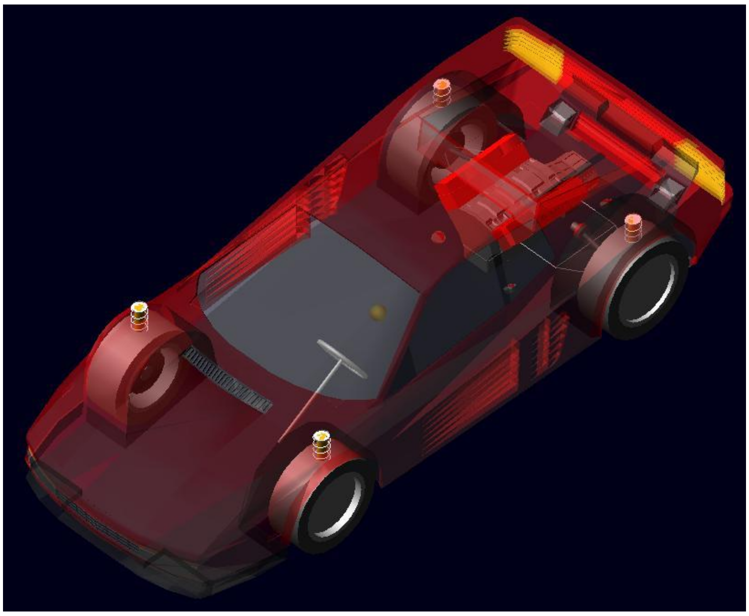


Figure 4.6.1: Assembly car model in ADAMS/Car used for the simulation process

The simulations are being performed solely to analyze and depict the amount of vibrations, or spring movements that a conventional car will encounter or experience when undergoing different road conditions and different driving characteristics. The simulations that are being performed are:

- Car during acceleration
- Car during braking
- Car being driven around a track ("Imola" track in ADAMS/Car)
- Car during cornering while braking

4.6.1 Simulation of Car Model during Acceleration

During a car's acceleration period, the author anticipates a significant amount of spring movements especially during gear changing. Figure 4.6.1.1 shows the parameters that are set for the simulation of the car model during acceleration.

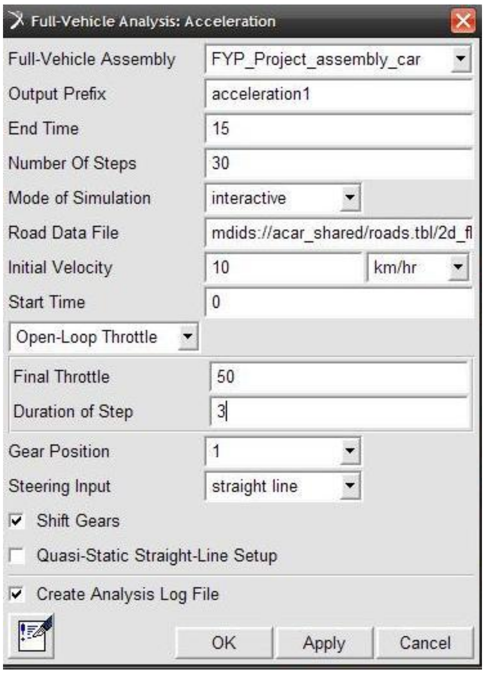


Figure 4.6.1.1: Parameters for the car model during acceleration

Basically, from figure 4.6.1.1, the car model is set to be at an initial velocity of 10 km/h where the simulation will end 15 seconds later. The car model is also capable of changing gears on its own when it is appropriate to do so. Final throttle of the car model is set to be at 50 percent.

As can be seen from figure 4.6.1.1, start time is set at 0. This means that as soon as the simulation begins, the acceleration phase for the car model will start as well.

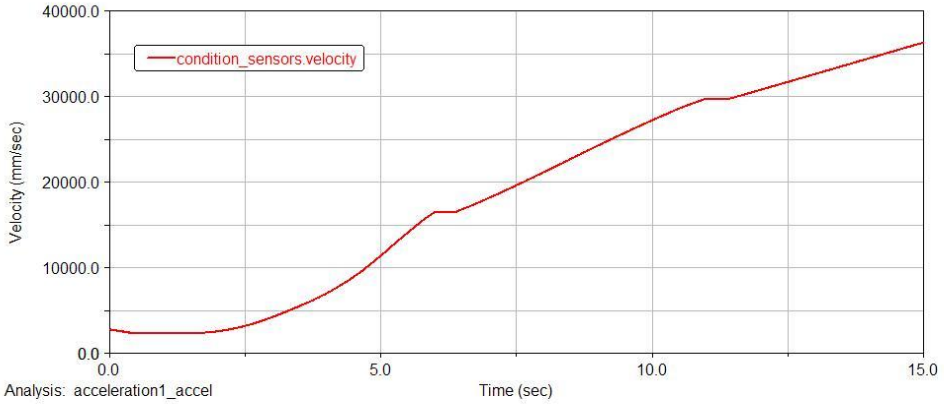


Figure 4.6.1.2: Graph of velocity versus time during acceleration simulation

Figure 4.6.1.2 shows the velocity curve of the car model during the simulation. The part in the curve where there is not a smooth line depicts the time when a gear is being changed.

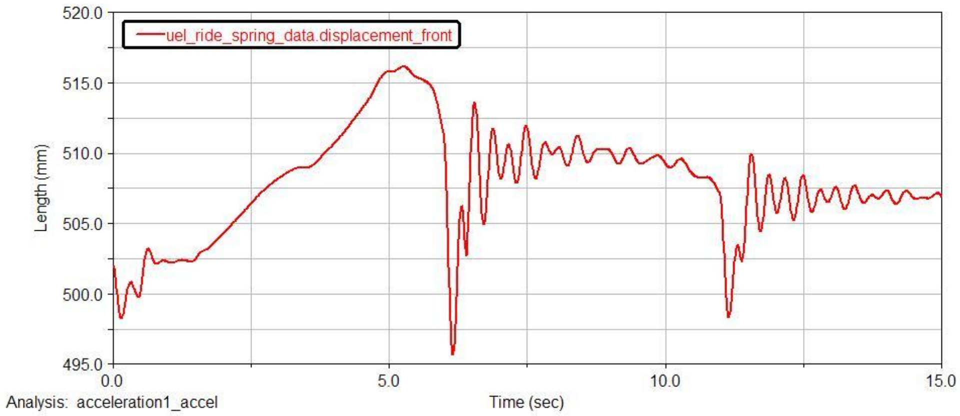


Figure 4.6.1.3: Graph of front spring displacement versus time

Figure 4.6.1.3 shows the front spring displacement versus time graph of the acceleration simulation. The spring's initial vertical location is measured to be at 501.98 mm. From the graph, the maximum and minimum length measured is about 516.15 mm and 495.69 mm which mean a spring displacement of around 14.17 mm and 6.29 mm respectively. There is no significant spring displacement difference between the left and right spring of the front suspension.

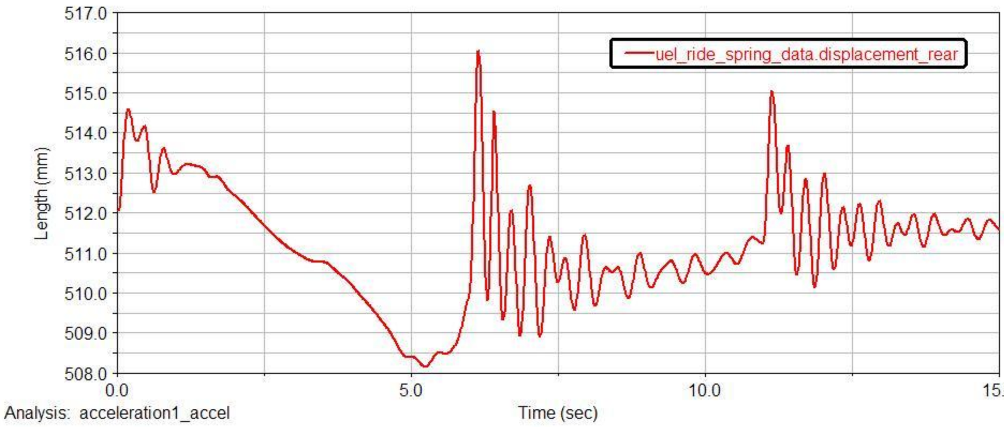


Figure 4.6.1.4: Graph of rear spring displacement versus time

Similarly, figure 4.6.1.4 depicts the spring's displacement at the rear of the car model. The spring's initial vertical location is measured to be at 512.05 mm. The maximum and minimum length measured is about 516.05 mm and 508.16 mm which in turns mean a spring displacement of about 4 mm and 3.89 mm respectively. Again, there is no significant spring displacement difference between the left and right spring of the rear suspension.

4.6.2 Simulation of the Car Model during Braking

When a car brakes, the author imagine a significant amount of spring movements due to the weight transfer of the car. Figure 4.6.2.1 below shows the parameters that are set for the braking simulation.

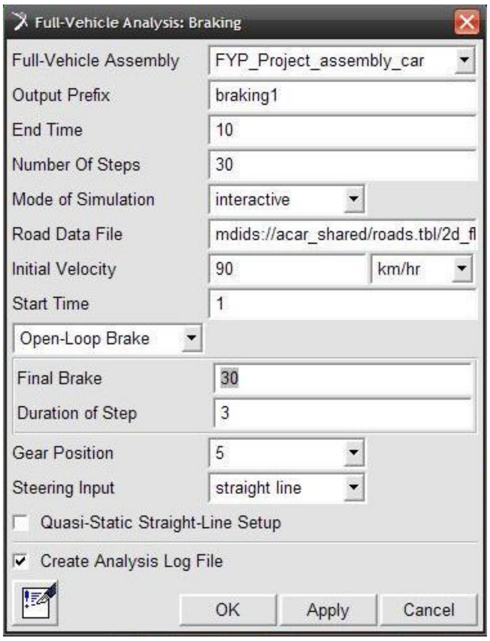


Figure 4.6.2.1: Parameters for the car model during braking

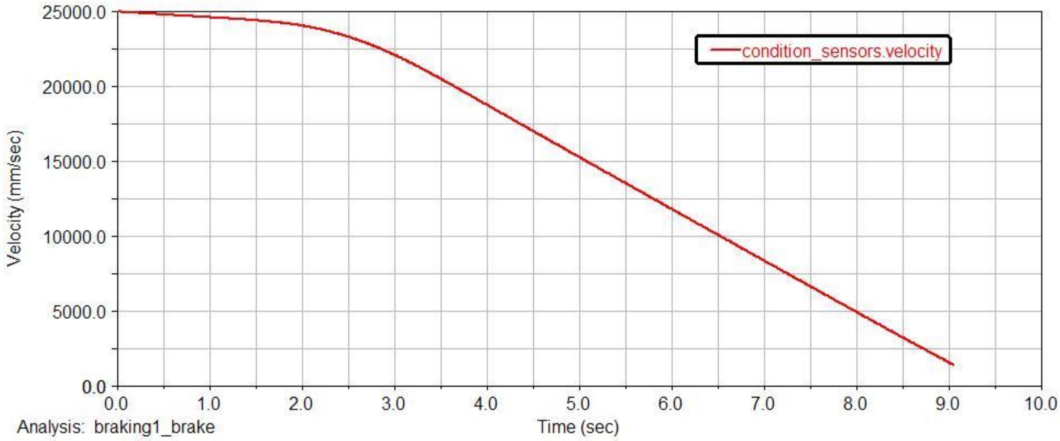


Figure 4.6.2.2: Graph of velocity versus time during braking simulation

Figure 4.6.2.2 depicts the velocity curve of the car model during a braking simulation. The car model goes from 90 km/h to roughly around 6 km/h in around 9 seconds during braking.

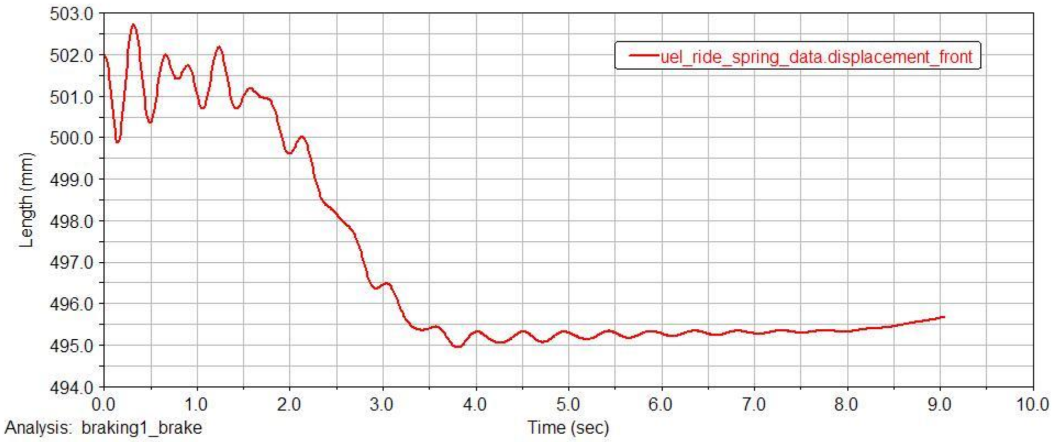


Figure 4.6.2.3: Graph of front spring displacement versus time

During braking, figure 4.6.2.3 shows the initial vertical location of the spring to be at 501.98 mm. The maximum and minimum length measured at the front spring is 502.73 mm and 494. 94 mm. This in turn shows a displacement of roughly 0.75 mm and 7.04 mm respectively. The left and right spring of the front suspension shows similar displacement values.

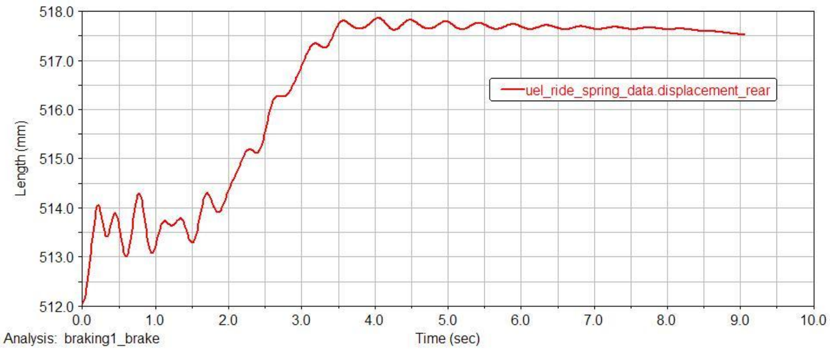


Figure 4.6.2.4: Graph of rear spring displacement versus time

Figure 4.6.2.4 shows an initial spring location of 512.05 mm. The maximum spring displacement here is around 517.86 mm, which calculates around 5.81 mm of spring displacement. The left and right spring of the rear suspension shows similar spring displacement.

4.6.3 Simulation of the Car Model in an Example Track – Imola

The author also performed a simulation of the car model being driven around a track to depict its characteristics, especially spring movements. The example track being chosen is named as “Imola”, which is already pre-installed in ADAMS/Car. Figure 4.6.3.1 shows the shape of the track which the car model will be driven using the Smart Driver analysis option from ADAMS/Car.

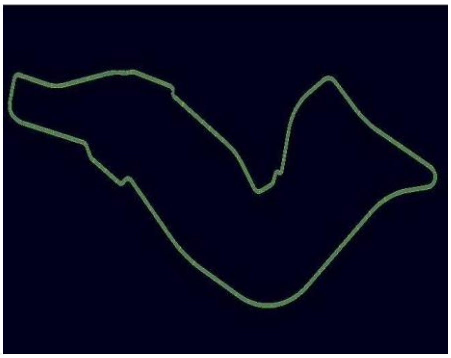


Figure 4.6.3.1: Shape of the “Imola” track in ADAMS/Car

The car model is set at an initial speed of 20 km/h at second gear. Utilizing the Smart Driver function found in ADAMS/Car, the car model will automatically change gears at the right suitable time. The car model is being set to follow the track direction automatically as well. Figure 4.6.3.2 shows the velocity curve or velocity profile of the car while being driven around the track for 50 seconds.

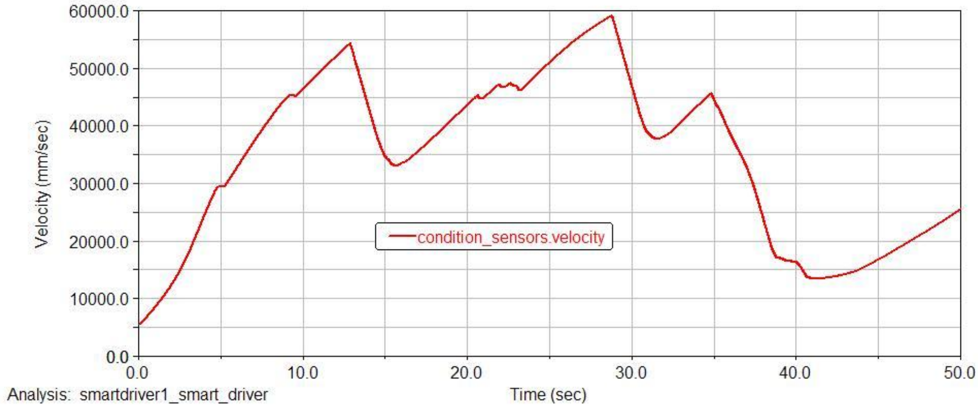


Figure 4.6.3.2: Graph of velocity versus time during simulation around “Imola” track

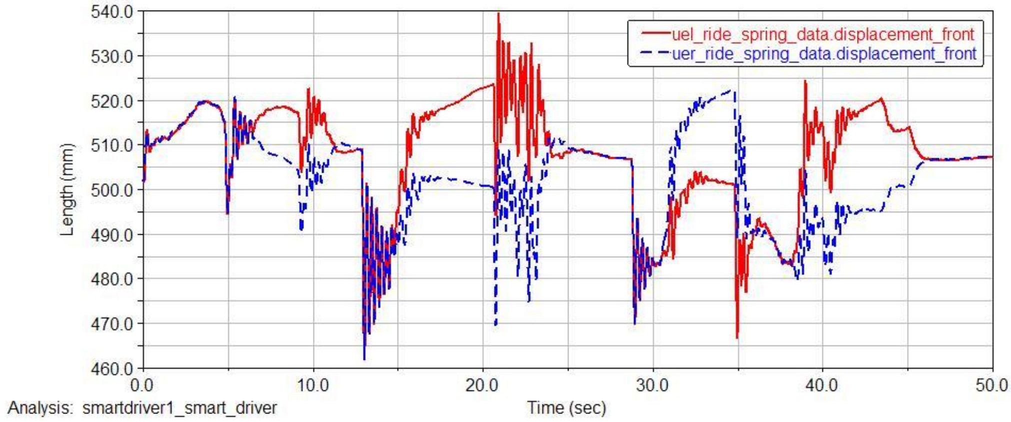


Figure 4.6.3.3: Graph of front springs (left and right) versus time during track simulation

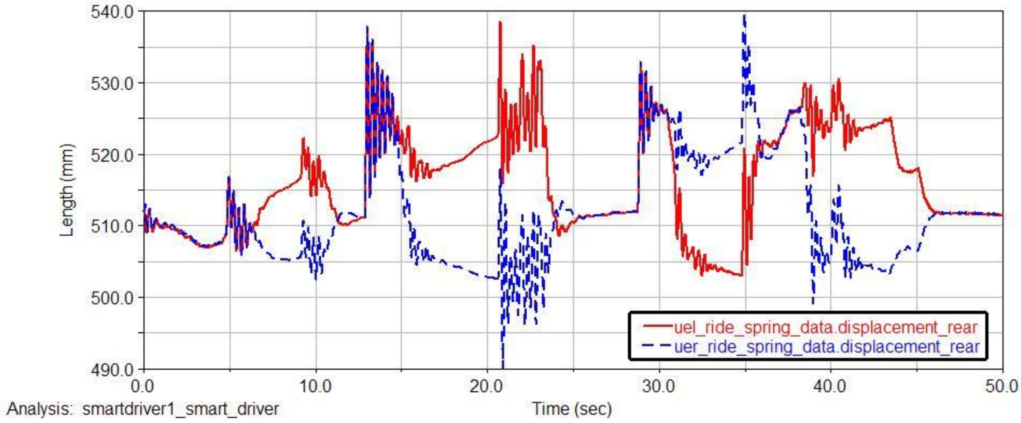


Figure 4.6.3.4: Graph of rear springs (left and right) versus time during track simulation

Figure 4.6.3.3 and 4.6.3.4 shows the comparison of spring’s displacements between the left and right springs of the front and rear suspension of the car model respectively. Generally, we can see that there will be an opposing displacement of the left spring when the right spring is being displaced in the other direction.

4.6.4 Simulation of the Car Model during Cornering while Braking

When a car goes through a cornering maneuver, there will be a significant amount of weight transfer from one side of the car to another due to inertia. Due to this phenomenon, there should be a considerable amount of vertical movements of the suspension when a car goes through corners. These loads should convert into useful regenerative energy from the suspension system. Figure 4.6.4.1 shows the parameters that are being set in ADAMS/Car to carry out the cornering while braking simulation.

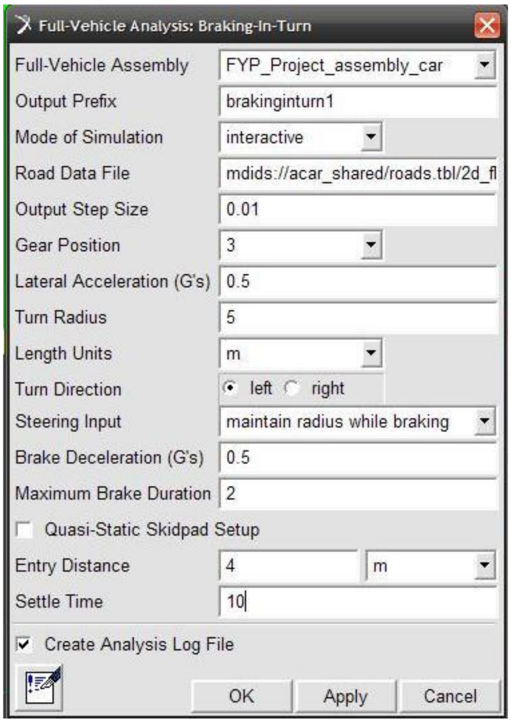


Figure 4.6.4.1: Parameters for the car model during cornering while braking

As we can see from figure 4.6.4.1, the car is set to be at gear three when entering the corner. As for lateral acceleration, it is being set at 0.5 G's. The brake deceleration limit is set at 0.5 G's as well. The turning radius of the cornering maneuver is set at 5 m. It can also be noted that the car model is being set to maintain its cornering radius while braking.

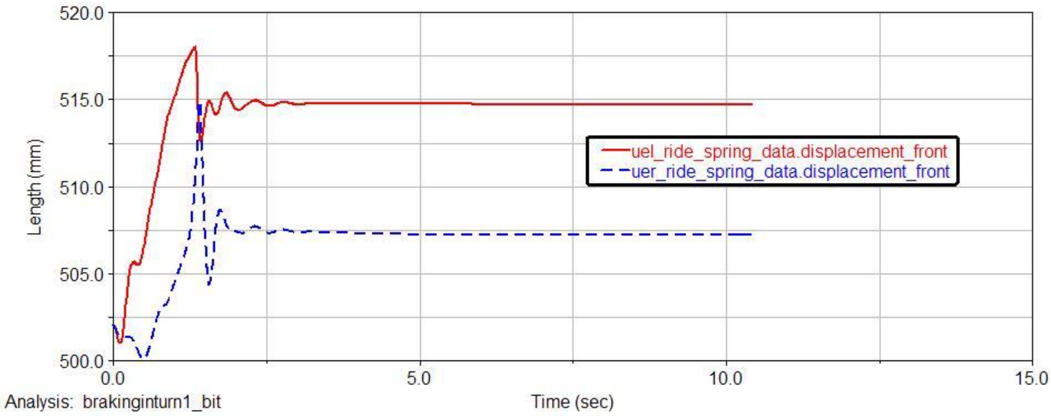


Figure 4.6.4.2: Graph of front spring displacement during cornering while braking for left and right suspension

Figure 4.6.4.2 shows the displacement of the front spring suspension during the cornering while braking maneuver of the car model in ADAMS/Car. The red coloured line represents the left spring while the blue coloured line represents the right side of the suspension. It can be observed that the excitations of the suspension only lasts for roughly 2 seconds from the start, as the braking duration is being set on purpose to be at 2 seconds.

As the car model is being set to turn to the left hand side direction, we can observe from figure 4.6.4.2, that the front left suspension is being extended more than the right suspension due to weight transfer to the right. Both suspensions undergo an excitation of around 15 mm at the start of the cornering, but stabilize very quickly after the car is in the corner.

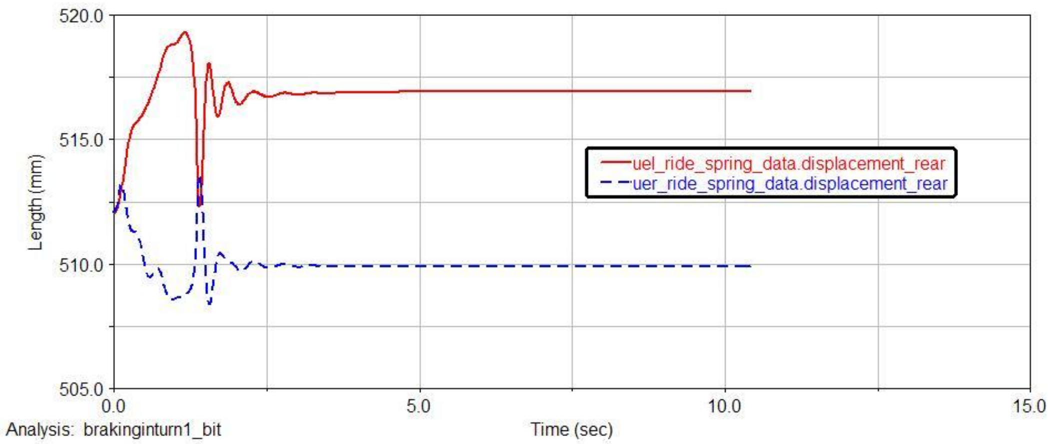


Figure 4.6.4.3: Graph of rear spring displacement during cornering while braking for left and right suspension

As for the rear suspensions, shown in figure 4.6.4.3, with red coloured line for left suspension and blue coloured line for right suspension, the graph looks more symmetrical. Both left and right of the rear suspension undergo around 6.3 mm of suspension excitation during the cornering while braking maneuver for around 2 seconds. After that, when time ≈ 2.5 seconds, the car stabilizes during the cornering maneuver which shows both suspension spring at a constant but different length, respectively due to weight transfer.

4.7 CALCULATIONS

As shown previously in section 4.3, the main equation that can be used to estimate the amount of energy that is possible to be saved is as shown below:

$$P_{\max} = V_e I \approx (\sigma_{Cu})(v_z^2)(B_r^2)(Volume_{coil})$$

<u>Example calculation</u>

$$P_{\max} = V_e I \approx (\sigma_{Cu})(v_z^2)(B_r^2)(Volume_{coil})$$

$$P_{\max} = V_e I \approx (\sigma_{Cu})(v_z^2)(B_r^2)(\pi \times [r_o^2 - r_i^2] \times h)$$

$$P_{\max} = (5x10^7\, S/m)(0.4m/s)^2 (0.29T)^2 \times \{\pi \times ([0.05m]^2 - [0.047m]^2) \times 0.003m\}$$

$$P_{\max} = \underline{\underline{1.845W}} \leftarrow$$ Estimated possible recovered energy per excitation of suspension (h ≈ 3 mm)

As shown in the example calculation above, the estimated amount of energy that can be regenerated by a 3 mm excitation of the magnet is around 1.845Watts. Bear in mind that h = 3 mm is just a value to fit into the example calculation. An important assumption is being made from this calculation. It is being assumed that the amount of vertical movement of the magnet is equal to the amount of vertical movement of the suspension system, similar to what is being analyzed in ADAMS/Car previously.

CHAPTER 5

DISCUSSION AND RECOMMENDATION

As an overall in this project, the author managed to perform a simple study and analysis on how the regenerative electromagnetic suspension works and what are the parameters that follows accordingly. However, the author did not really achieve his planned objectives as a whole in the end. Therefore, the author recommends future work to be continued on this project as it is quite a feasible project to be worked on.

The author hopes that in the future, one is able to program this whole project along with its equations and parameters into ADAMS/Car in such a way that one is able to plot a graph which shows the amount of recovered energy versus the amount of suspension excitation directly. This will definitely give a more accurate indication of the feasibility of a regenerative electromagnetic suspension system in a vehicle.

Apart from that, the author hopes that future work will also concentrate on the amount or quantity of damping force that the electromagnetic suspension is able to generate. This is due to the fact that, the damping force is actually a repulsive force from the electromagnetic system itself. Therefore, much consideration is needed on this matter as it will affect the overall efficiency of the regenerative electromagnetic suspension system.

CHAPTER 6

CONCLUSION

As a conclusion to this report, the author wrote about the development of hybrid vehicles in the automotive world today. One of the developments of hybrid systems is the potential of recovering from the shock absorbers in a car suspension system itself. It is a process of recovering energy from damped, vibrating suspension system of a car. This emerged due to the need of the automotive world today for continuous improvement of vehicle's energy efficiency, and the potential benefits from the development of regenerative vehicle suspension systems. The objective of this paper is to perform a study and analysis on regenerative suspension systems utilizing magnetic shock absorbers to harness those otherwise lost energy in a conventional vehicle suspension system. The author analyzed different suspension excitations on various selected driving environments using the ADAMS/Car software. The author then performed detailed analysis on the governing equations in order to carry out related calculations in estimating the amount of energy or power that can be recovered from the electromagnetic suspension system. Last but not least, the author proposed a few feasible suggestions for future work on this project to look into the efficiency of this regenerative suspension system.

REFERENCES

1. Xuechun Zheng & Fan Yu. (2005). *Study on the Potential Benefits of an Energy-Regenerative Active Suspension for Vehicles*. SAE Technical Paper Series.

2. B. Ebrahimi, M. B. Khamesee & M. F. Golnaraghi. (2008). *Development and Modelling of a Novel Electromagnetic Damper*. ASME Information Storage and Processing Systems Conference. USA.

3. R. B. Goldner & P. Zerigian. (2001). *A Preliminary Study of Energy Recovery in Vehicles by Using Regenerative Magnetic Shock Absorbers*. SAE Digital Library.

4. A. Gupta, J. A. Jendrzejczyk & T. M. Mulcahy. (2007). *Design of Electromagnetic Shock Absorbers*. Springer Science+Business Media B.V. 2007.

5. M. G. Fodor & R. C. Redfield. (1992). *The Variable Linear Transmission for Regenerative Damping in Vehicle Suspension Control*.

6. Kynan E. Graves. (2000). *Electromagnetic Energy Regenerative Vibration Damping*.

7. Prof Amarnath, Kaushik J & Ankit Mehta. (2005). *Regenerative Shock Absorber.*

8. Jefferson, C. M., & Barnard, R. H. (2002). *Hybrid vehicle propulsion*. London: WIT Press.

9. *Types of Magnets*, < http://www.coolmagnetman.com/magtypes.htm >