Review of Methods for Energy Harvesting from a Vehicle Suspension System

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Preface

This report focuses on already existing literature in the field of energy regeneration, more specifically in vehicle suspension systems. The findings in this report are therefore not new but the evaluation and comparison of the information is.

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Abstract

With the increasing population the energy consumption has increased which makes the requirement for clean energy important, now more than ever. The transport sector is one of the biggest contributors to this consumption and should therefore be taken into consideration when looking for environmentally friendly solutions. The majority of fuel energy in road-bound vehicles of today is dissipated and is therefore never utilized. For a passenger car traveling at $13.4\,\text{m/s}$ it is found that $200\,\text{W}$ worth of energy is lost in the vehicles suspension system.

The purpose of this work is to analyze and evaluate existing methods for energy regeneration from vehicle suspension systems in order to identify the most optimal solution. To end with, the report will propose mathematical models for simulations of the chosen system.

This report examines electrostatic, piezoelectric and electromagnetic methods of energy regeneration and it is concluded that electromagnetic generators are the most viable when applied to vehicles. Furthermore, already existing ideas for regenerative suspension systems using electromagnetic generators are explained and compared. It is concluded that a suspension system using an electromagnetic generator coupled with a magneto-rheological (MR) damper is the most optimal when looking at efficiency, cost, robustness and environmental impact. It can generate up to $90\,\text{W}$ and is shown to be the most robust system because of its few moving parts. The working principle of the regenerative electromagnetic MR damper is explained and mathematical models describing the characteristics of the MR damper and the electromagnetic generator, based on previous work, are proposed. A simulation model using a quarter-car model is also proposed where different methods of road profile generation are suggested. The environmental aspects of the regenerative MR damper is conclusively discussed and evaluated so that the overall environmental performance of the system can be decided.
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1 Introduction

One of the biggest issues faced today when it comes to sustainability is the energy crisis which has led to great challenges in the development of energy efficient and environmental friendly solutions of everyday life. One of the largest areas of concern is the transport sector which has already seen great improvement in recent years. When looking at road-bound vehicles only 14-30% [1] of the fuel energy is used for the mobility of the vehicles. A large amount of the consumed energy is dissipated into heat through vibrations. So a way of reducing the energy consumption would be to harvest some of the energy that is dissipated.

1.1 Aim

The aim of this report is to determine what possibilities a regenerative suspension system has for improving the energy consumption in vehicles.

1.2 Method

The aim of this report will be achieved through the following steps:

- Perform a literature review
- Compare the most promising solutions
- Analyze the most optimal solution
- Propose mathematical models for the chosen system
- Discuss the sustainability of the system.

1.3 Outline

This report is based on a literature survey covering previous work in the field of energy harvesting. Initially, the issue with low energy efficiency in vehicles is discussed in Chapter 1 and it is explained why a regenerative system would help to solve this problem. Some of the recent research and development in the field of energy harvesting is covered in Chapter 2 to obtain a comprehensive overview of the field. After looking at some of the conventional methods used the report continues by comparing the more promising technological solutions proposed by the studied literature in Chapter 3. The different methods for energy regeneration are compared and the efficiency of these based on the amount of harvested energy, potential production cost, robustness etc. is evaluated. The most prominent technology is further analyzed and mathematical models are presented in order to describe the given system in Chapter 4. Possible limitations with the proposed models is taken into consideration in order to determine the validity of the modeled system. The sustainability of the system is thereafter determined in Chapter 5. This is done by putting the regenerative capability of the proposed system in perspective to other environmental factors affected by the system. Finally, conclusions are drawn in Chapter 6, based on all the gathered data and information, regarding what possibilities the energy harvesting technology have for the society.


2 Literature review

One of the major applications of the wheel suspension system is to prevent the vibrations of the wheel, caused by road roughness, to be transferred to the vehicle body. This is done by having a damper that absorbs the energy from these vibrations. According to simulations carried out by Segel et. al. [2] a passenger car traveling on a poor roadway at 13.4 m/s dissipates approximately 200 W worth of energy only from the dampers on the car. If the mechanical energy, on the other hand, could be converted to electrical energy and redirected into different features of the vehicle it would provide less dissipation of energy. This conversion can be done with the help of, for example, an electromagnetic generator. Depending on the construction of the suspension system this electromagnetic generator can either be rotary or linear.

There are a variety of different methods to achieve the conversion of energy. Zhang jin-qiu et. al. [3] compares different electromagnetic regenerative suspensions. An example of a suspension system that utilizes a linear electromagnetic generator is the direct-drive electromagnetic suspension [4] which turns linear motion caused by vibrations into electrical energy needing no transmission. Ball-screw and rack-pinion electromagnetic suspensions, on the other hand, converts the linear motion into rotational, using a mechanical transmission. It is this rotational energy that then is converted into electrical energy using a rotary electromagnetic generator. Nakano [5] proposed the use of self-powered ball-screw active vibration control in truck cabins and a simulation was carried out. According to the simulation, it was found that the dampers on the cabin was exposed to 87.02 W worth of vibrational energy and that 31.63 W could be regenerated and stored. This means that the efficiency of the system is 36 % which is shown to be enough for the system to be self-powered. Zhang jin-qiu et. al. [3] reached the conclusion that the self-powered magnetorheological (MR) damper and the hydraulic transmission electromagnetic (HTE) suspension are the most effective ones. An MR damper is a damper that functions by having an electromagnetic field run through the MR fluid in the damper and thereby regulate the dampers stiffness. This process requires electrical energy and is therefore greatly improved when made self-powered by integrating an electromagnetic induction (EMI) device into the damper system. A downside of this structure is that the damper can not work with full efficiency during the regeneration process, making it mainly applicable in semi-active damper systems. The HTE suspension functions by combining a hydraulic transmission with an electric motor. Displacement of the wheel forces the piston inside the suspension to move and set the hydraulic fluid in motion. The fluid in turn causes the motor to rotate and generate electrical energy. Just like the self-powered MR damper the regenerative process of the HTE suspension only works while in semi-active state and just like the self-powered MR damper the main use of the regenerated energy is to power the damper system. Both the HTE damper and the MR damper are active damper systems which actively work to suppress vibrations. Levant Power Corp. [6] have developed a HTE suspension, GenShock, which they claim decrease the fuel consumption of military vehicles by up to 6 %.

In comparison to the electromagnetic energy harvesting shock absorber Q. Wang et. al. [7] introduced the dual-mass piezoelectric energy harvesting shock absorber (PESHA) as an alternative. The principal design of this dual-mass PESHA consists of a spring, a lever, a fixed hinge and a piezoelectric bar. When the piezoelectric material (PZT-4) is deformed it creates an electric field that can be redirected and the electrical energy can be stored. Despite this being a relatively new field of use for the piezoelectric energy harvester, there are other proposed system designs. According to Hyeoung Woo Kim et. al. [8] the piezoelectric "cymbal" transducer is designed to cause less exhaustion to the piezoelectric bar and thereby increasing its life span. It is of importance that the system is mechanically stable because of the high cyclic stress it is exposed to. Hongseok Lee et. al. [9] proposed a piezoelectric system consisting of two parallel plates integrated in a vehicle shock absorber. When exposed to a load, the piston inside the shock absorber compresses the damping fluid and creates a pressure which in turn deforms the installed piezoelectric plates, thus transforming mechanical energy into electrical. Although the experimental results showed a moderately small amount of generated
energy it was discussed that it was due to the fabricated system being a 1/10 scaling of an actual size application.
3 Review and comparison of existing solutions

The idea of regenerating dissipated energy into useful electrical energy has been around for a while and often it is vibrations that dissipate in the form of heat energy. The idea is to make use of kinetic energy in the ambient vibrations and regenerate it as electrical energy. Three of the most established methods of achieving this are electrostatic, piezoelectric and electromagnetic. Electrostatic transducers operate by having the overlapping distance between two electrodes of a polarized capacitor change when the system is exposed to vibration. The introduced movement causes the voltage inside the capacitor to change and thus gives rise to a current flow, which, with an external circuit, can be extracted. The piezoelectric transducers utilize external vibrations to deform a piezoelectric ceramic, causing a voltage in the capacitor to arise and thereby generating electric power. Finally, the electromagnetic transducers use the relative motion between a magnet and a coil to change the magnetic flux in the system. This generates an alternating current and voltage across the coil.

Although the piezoelectric method of converting mechanical energy into electrical is shown to be very effective [7], the application for vehicle suspension systems is yet to be thoroughly tested. The biggest advances for the scientific field of piezoelectricity seems to be in microscopic applications, such as the development of MEMS [10]. The same is argued by Beeby et. al [11] for the electrostatic generator; they too are best suited for MEMS-applications.

Compared to piezoelectric and electrostatic methods of use, there is a lot of literature reviewing the use of electromagnetic transducers applied to vehicle suspension systems. Systems such as the ball-screw and rack-pinion suspension system, hydraulic transmission electromagnetic system, linear electromagnetic system and regenerative magnetorheological (MR) damper systems are some that has been acknowledged. These different types of electromagnetic systems will be reviewed and compared in this section so that the most promising solution, with respect to the application of vehicle suspensions, can be established and further analyzed.

3.1 Ball-screw electromagnetic energy harvester

Nakano [5] proposed a ball-screw electromagnetic damper to be used for regenerating energy from an active truck cabin suspension system and then using that energy to power the system, thus making it completely self-powered. The article discusses the feasibility of the system being self-powered by examining the balance between the regenerated and the consumed energy of that system. The electromagnetic damper model used for this study consists of a DC motor, a ball-screw and a nut (see Figure 1). The linear motions of the damping system caused by ambient vibrations is converted into rotational motion by the ball-screw and nut configuration. The rotational motion transferred to the motor induces a voltage which generates a current that is stored in an electric double layer capacitor as electrical energy.

The energy regenerative damper and the actuators, located at the front and rear suspensions of the truck, are connected to the same capacitor through relay switches. The circuits connecting the actuators include variable resistors which are operated by an external computer. This allows for the electric...
current to be controlled so that a desired continuous motor force can be obtained, making the damping system fully active. Simulations carried out showed that the average regenerated and absorbed energy during a period of 20 seconds were 31.63 W and 55.39 W, respectively. This gave an efficiency of 36%. These values were obtained with the assumption that the energy loss in the variable resistor is neglected. When analyzing the actuators output power, while powered by regenerated energy, it was shown that the actuators followed the desired output force well except for when the external forces on the system became to large. This causes a deterioration in isolation performance. It was concluded that the reason for the insufficient output force was due to a deficient capacitor voltage not sufficiently raised by the regenerating damper. Despite the lack of actuator output power, the proposed system out-performed both a competing semi-active and passive system.

3.2 Rack-pinion electromagnetic energy harvester

Li et. al. [12] suggested the use of an electromagnetic energy harvesting shock absorber with a rack-pinion mechanism. The principle design of the shock absorber utilizes a rack and pinion to transform linear motion into rotational (see Figure 2).

![Figure 2: The energy harvesting shock absorber with rack-pinion mechanism [12].](image)

With the use of a bevel gear the transmission is changed 90° and the rotation can be transferred to the motor via a planetary gear. If the transmission ratio is chosen to be high the system can achieve a high damping coefficient but this is limited by the fact that a large transmission ratio leads to a low transmission efficiency. The choice of gears is very important because they are often the cause for failure not only because of fatigue but also because roughness on the cog teeth can interfere with the regeneration performance. There is also friction and backlash impacts in the system. In order to reduce this the article suggest a roller that guides the rack. Teflon rings were also used between the inner and outer cylinders to further reduce friction. The article used a permanent magnetic DC motor as a generator. Even though this shock absorber was designed to be passive the article mentioned that active suspension characteristics could be implemented by keeping the regenerative shock absorber exposed to different electrical loads. Bench tests were performed and it was discovered that the amount of regenerated power is dependent on the vibration frequency and electrical load from the power charge circuit. The system was then installed in a Chervolet Surburban SUV (2002 model) and a road test was performed on an asphalted campus road at a speed of 48 km/h and an electrical load of 30 Ω. The rack-pinion energy harvester had a peak power of 67.5 W and an average power of 19.2 W with a total energy conversion efficiency of up to 56%.

3.3 Hydraulic electromagnetic regenerative damper

Both the ball-screw and rack-pinion mechanism, when used in energy regenerative shock absorbers, causes the rotational direction of the generator to constantly change depending on if the shock absorber is compressing or expanding. This constant change of rotational direction has a negative effect on the generator and can be the cause for failure in the long term. The hydraulic transmission electromagnetic energy regenerative active suspension was suggested as a solution to this by Lin et. al. [13]. The
generator in this system is put in motion by a hydraulic fluid and has a constant rotational direction regardless of if it is exposed to a compression or expansion.

Figure 3: The hydraulic transmission electromagnetic energy regenerative active suspension [13].

When this system is exposed to compression the piston (1) (see Figure 3) together with the plate (4) creates enough pressure in the piston working cavity to force the hydraulic liquid through the non-return valve (11) and travels through the high-pressure pipe (9) until it reaches another non-return valve (12). Through this valve, the liquid reaches the electricity-generating cavity where it, with the help of the energy accumulator (6), will set the hydraulic motor (7) into motion which in turn will drive the electric generator (8). It is during this phase that the reacting force from the electric motor causes the hydraulic motor to produce the damping force to the liquid which is the majority of the shock absorbers damping force. After passing through the hydraulic motor the liquid passes through the low-pressure pipe (5) to reach the non-return valves (2) and (3). This process makes sure that the liquid flow is always in the same direction when passing through the electricity-generating cavity which in turn causes the electric generator to have a constant rotational direction.

Lin et. al. [14] performed experiments on this system and found that it, despite its promising design and impressive simulation results [15], proved to be relatively inefficient. The experiment showed that the system only recovered 16.5% of the vibrational energy it was exposed to. When developing the system, the authors had not initially accounted for the linear loss. The report showed that the linear loss of the oil accounted for 1/3 of the total energy. However, based on the mathematical model of this loss, included in [14], it can be reduced significantly by increasing the inner diameter of the pipeline. Even though this systems fundamental purpose was to reduce the energy loss in the generator from the constant change of rotational energy, the report showed that 21.1% of the energy was lost in the hydraulic motor and the generator. The remaining energy loss is accounted for by the hydraulic rectifier and other local losses.

### 3.4 Linear electromagnetic energy harvester

The linear electromagnetic energy harvester transforms the kinetic energy of a linear motion into electrical energy through a permanent magnet generator. The magnet assembly typically consist of permanent magnets and coils. In order to obtain good regeneration a key factor is to maximize the magnetic flux density through the coils. The current in the coil is created by relative movement between the magnets and the coils. One way of maximizing the magnetic flux is to implement highly
permeable materials so that the reluctance of magnetic loops decreases. Zuo et. al. [16] designed and tested a regenerative shock absorber in the configuration of a linear generator. An important aspect of the regeneration system is the phase in which the coils in the linear energy harvester are positioned. All adjacent coils are phased $90^\circ$ from each other making each set of four coils one four-phase configuration (see Figure 4). The linear energy harvester is made up of four of these sets making a total of 16 coils. The four-phase configuration provides a more even regeneration of electricity with one pair of the four-phase setup always in correspondence with the magnetic loops.

Figure 4: Diagram of the four-phase generator configuration with coils moving in the magnetic field during the vibrations of the vehicle suspension [16].

The tested prototype of scale 1:2 showed promising results. An estimated translation to a full-scale model in a suspension application would correspond to $16-64$ W at $0.25-0.5$ m/s RMS suspension velocity. It was shown that the 1:2 scale system attained its best regeneration capabilities at around 10 Hz with an almost linear relation of 1:6 between the input voltage for the attached shaker system and the output voltage of the regeneration system. After incrementally raising the input voltage to around 1.5 V the relation stagnates. The regenerated power will be largest at around the resonance frequency of the system.

Another method of achieving a higher magnetic flux density is by optimizing the thickness $\tau_{ma}$ of the magnets in the axial direction and the thickness $\tau_{cr}$ of the coil in the radial direction [17]. The average magnetic flux will decrease when $\tau_{cr}$ is increased because this will lead to a bigger air gap which in turn will cause a disruption in the magnetic field. However there is a optimal $\tau_{ma}$ for a constant $\tau_{cr}$ which means that when designing the shock absorber the coil thickness in the radial direction should be as small as possible and the thickness of the magnets in the axial directions should be chosen accordingly.
The magnet arrangement also has an influence on the magnetic flux. The arrangement of [16] can be seen in Figure 5 (a) where axial magnets are used coupled with iron spacers. Figure 5 (b) shows a configuration where radial magnets are used instead of the steel spacers which leads to a higher density of the magnetic flux. Radial magnets are a new type of magnet that are magnetized in the radial direction and can therefore increase the radial flux density. Another configuration is the double-layer configuration (see Figure 5 (c), (d)) that provides better guiding of the magnetic flux and can be implemented in both the shock absorber that used iron spacers and the one that uses radial magnets. [17] shows that 26 W and 33 W can be generated when using single-layer respectively double-layer configuration with both axial and radial magnets.

3.5 MR electromagnetic regenerative damper

Finally, the MR damper system suggested by Chen et. al. [18] is a self-sensing, self-powered, controllable system where the power-generation and sensor function systems are integrated into the MR damper itself. Integrating the systems leads to large space and weight reduction, cost-effectiveness, reliability and less maintenance compared to keeping the different arrangements separated, as previously conducted by papers investigating MR dampers. The proposed system was simulated and a prototype was tested in experiments. The experimental data matched well with simulations and theory for all the examined functions comprising damper control ability, power generation and sensor functionality. A cross-section of the fully assembled damping system is found in Figure 6. The vibration that is imposed on the system causes the piston rod to move linearly. The power part and the sensor part of the system are both directly attached to the rod and are therefore moving with it. The power part
is consisting of primarily permanent magnets and coils. Because the inner layer of the power part is attached to the moving rod a relative velocity occurs between the inner layer and the outer layer of the power part. This causes a change in magnetic flux which in turn generates electrical power. The sensor part is primarily consisting of a coil and a magnetized ring. When it moves with the rod it generates a change in the magnetic circuit. As established by Faraday’s law of electromagnetic induction the movement will generate an electrical voltage in the coil which is proportional to the velocity of the sensor. By measuring the voltage the velocity of the moving rod can be obtained. The damping ability of the MR damper is attained by the MR fluid located in the damping part. The fluid exhibits a fast transition from a liquid state to a semi-solid state in a matter of milliseconds when exposed to an external magnetic field. This fast transition and the ability to measure the suspension velocity using the sensor is what makes the damping force controllable and effective. The regenerative ability of the power part is what makes the entire system self-powered and thus highly efficient.

![Sectional view of the self-powered, self-sensing MR damper](image)

The experiment showed that the amount of power which could be generated and used for damping load in a vehicle suspension with the relative squared velocity of \(0.04-0.36 \, (m/s)^2\) was \(10-90 \, W\). It was also shown that as the current to the damping controller increases, the damping force increases gradually until it finally levels, due to saturation of the MR-liquid. The amount of damping force that one MR damper could generate was about \(2560 \, N\) with an induced current of \(1 \, A\).

### 3.6 Comparison

The five analyzed systems can be categorized in two different sections, rotational and linear based. The rotational systems are the ball-screw, the rack-pinion and the hydraulic regenerative systems. The remaining linear and MR systems are identified as linear based. Besides the necessity of being able to regenerate enough energy these systems also need to be small, durable and inexpensive. They need to be small enough to be implemented in existing vehicles, durable enough to withstand the impacts of the road and inexpensive enough to interest customers.

When comparing the rotational based systems it can be stated that there are a few differences between the ball-screw and the rack-pinion systems that makes the ball-screw more favorable in a suspension aspect. The ball-screw system can generally be made smaller than the rack-pinion due to its simple construction. This is a major advantage because fewer working components usually means a lower cost and higher durability. The ball-screw also has a higher transmission efficiency than the rack-pinion, making it more suited for a regeneration application. This is because the ball-screw model
only utilize one transmission level while the rack-pinion have three, including a planetary gear inside the motor. A greater number of transmission levels equal larger energy loss since each level dissipates energy through friction. In conclusion it is, based on these criteria, decided that the rack-pinion configuration is not the optimal solution. The remaining rotational based system that must be compared with the ball-screw configuration is the hydraulic regeneration system. This system utilizes the fluid pressure for the conversion of kinetic energy into electric. Obvious benefits with this system, compared with ball-screw, is that the rotational direction doesn’t change with the change in linear motion of the piston following the external vibration. A frequent alternation of rotational direction can cause damage to the harvester which leads to lesser reliability. Because the ball-screw system utilizes energy transformation through movement of solid components it is more fragile to sudden bump excitations than the hydraulic system using fluids. This is due to the fact that the gears are prone to potential damage when exerted by large forces; unlike the hydraulic system where the fluid itself is damping the forces. Although the hydraulic system is more robust than the ball-screw it is shown to be less energy efficient due to an extensive loss of energy largely caused by friction between the fluid and the surrounding container. Compared to the 16.5 % power regeneration efficiency of the hydraulic system the ball-screw energy harvester with its 36 % is clearly dominant. Note that the efficiency value of the ball-screw generator is obtained from simulations and not experiments. The ball-screw can also be made much smaller than the hydraulic system due to the simplicity of the design. The ball-screw is the rotational based design that is the most optimal.

The regenerative MR damper and the linear energy harvester are very similar when it comes to their regenerative characteristics which means that they have similar strengths and weaknesses in that regard. Both systems have significant magnetic flux leakage which leads to a loss of potential regenerative efficiency. Also as previously said the most efficient linear generator is the double-layer configuration with both axial and, the more expensive, radial magnets. This means that the energy harvesters will increase in size and in cost. What sets these two apart is their damping characteristics. The linear energy harvesters gets its damping from the electromagnetic generator itself which at times could be insufficient to provide comfortable damping or inefficient enough to not be self-powered. The MR damper on the other hand can, with the help of the MR liquid, generate a large damping coefficient which ensures comfortable damping. Another feature that sets the regenerative MR damper apart from the linear energy harvester is its self-sensing system. This system causes the MR damper to react faster to changes in the speed which leads to improved damping. It also prevents energy waste due to it ensuring the damper is just as stiff as it needs to be. It is also integrated into the damper in a way that doesn’t call for an external system to drive it which leads to faster response and a more compact construction. The linear energy harvester is not a good enough replacement for a vehicles damping system on its own but can be improved when installed in an MR damper.

When comparing the ball-screw energy harvester and the self-powered MR damper it can be shown that the MR damper has a higher reliability. This is due to its components not being exposed to the same type of mechanical wear as the ball-screw is, such as bump excitations. Having the kinetic energy alternating in direction when driving the generator, as is the case for the ball-screw mechanism, has the potential of causing damage to it. This is avoided using the linear regenerative MR damper since the system that it uses is based on linear kinetic energy conversion. Another advantage of the linear motion in the regenerative MR damper is that there is no inertia loss resulting from frequently alternating the rotational direction. This in turn maintains regeneration efficiency and suspension performance. The vibration control ability of the MR damper is exceeding that of the ball-screw with it being able to react up to a 1000 times per second [19]. The MR fluid also has the ability of becoming close to solid which ensures a high range of damping force, that is adjustable with high precision by changing the overlapping magnetic flux. The MR damper has a low power requirement since the MR fluid doesn’t require a large amount of power to generate the magnetic flux needed for the damping, which in turn increases its power efficiency. LORD Corporation offers automotive suspension systems that uses MR damping and states that the dampers max power requirement does not exceed 20 W
In comparison, the ball-screw system suffers some decrease in regeneration efficiency due to the amount of power needed for the generator (motor) in the harvester to generate enough damping force. A disadvantage that the MR system has compared to the ball-screw system is its size and weight difference. The simplicity of the ball-screw design leads to a smaller and lighter product whereas the regenerative MR damper consists of a more complex system that causes it to be greater in size and weight. Another disadvantage of the MR damper system is its production cost due to the expensive MR-fluid which is a problem the ball-screw system, with its inexpensive design, doesn’t face. These advantages that the ball-screw system has over the MR system are affective but not deciding factors in the choice of the system for this report. The weight- and size issue of the MR damper system is not definitive for it to not be installable in vehicles today.
4 The regenerative MR damper and its working principals

The conventional MR damper has already seen application in a variety of vehicle models by companies such as Audi, Porsche, Ferrari, Lamborghini, Chevrolet, Cadillac, Ford, Range Rover etc. [21–24]. One of the most widely used products on the market is the MagneRide system developed by BWI Group [25], which is an MR damper configuration. Although the MR damper technology is already established on the market, the application for regenerative MR systems has yet to be sufficiently introduced. Despite the current situation, the demand might change in the coming years due to the increasing trend for active suspension systems. Although an active system enables high comfort through precise control of stability, it requires powering by the battery. Implementing a self-powered, active suspension system in the form of a regenerative MR damper will therefore be attractive for the vehicle manufacturers and also for the preservation of the environment.

This chapter studies the regenerative MR technology more thoroughly by investigating the fundamentals of the MR fluid as well as the system and its working components. It also gives a description of the vehicle system which the MR damper is implemented in. This will lead to a more comprehensive understanding of the regenerative damper which is desirable in order to reach a valid conclusion regarding the systems functionality when applied to a vehicle suspension.

4.1 The MR fluid

The Magneto-rheological fluid (MR fluid) is, as described by Goldasz [26], a suspension of fine, non-colloidal, low-coercive ferromagnetic particles in a carrier fluid. This fluid belongs to the class of controllable liquids which has the ability to change from a liquid state to a semi-solid state with a yield stress in the matter of milliseconds when exposed to an external magnetic field. What makes this fluid so applicable for a vehicle suspension system is that it is controllable, reversible and fast reacting. It also fulfills the important performance criteria of having a low initial viscosity, high shearing ability when reacting to the magnetic field, low hysteresis, temperature stability and most importantly; low power consumption.

When a magnetic field is applied to the MR fluid the solid particles dispersed in the fluid, created by a number of sub-domains with initially randomly aligned dipole moments (see Figure 7), starts to become ordered. This causes the sub-domains in a particle to align in a single direction creating magnetic forces between the particles. This in turn generates chain-like structures in the direction parallel with the magnetic field (see Figure 8). The particles will attract each other parallel to the magnetic flux and repel each other in the perpendicular direction.

![Figure 7: MR fluid particles when off-state](image)
Figure 8: MR fluid particles when on-state [26]

With the particles structured the fluid exhibits a yield stress which is dependent on the magnetic field. The fact that the fluid receives an increased yield stress is what makes the damping effect in the system possible. The rate at which the particles in the fluid form the chain-like structures is mostly depending on the rate of which the magnetic field can increase and organize the particles. The yield stress of the MR fluid can be increased by adjusting the particle density or by adjusting the magnetic flux density [27]. Adjusting these parameters will lead to thicker particle structures that can withstand higher forces and thus provides higher damping capability.

4.2 Quasi-static analysis of an MR damper

When analysing an MR damper as a quasi-static system three assumptions are made [28]; (1) the MR damper is moving at a constant velocity, (2) the MR fluid is fully developed and (3) a simplified Bingham model of plasticity is used. The Bingham model, when applied to an MR fluid, gives the relation between the shear stress and shear rate as [26]

\[ \tau = \tau_0 + \mu \frac{\partial u}{\partial x}, \]

where \( \tau_0 \) is the yield stress caused by the magnetic field, \( \mu \) is the post-yield viscosity and \( \frac{\partial u}{\partial x} \) is the shear rate. The fluid in the damper flows through an annulus and can be analysed by either using an axial symmetric model or a parallel-plate model (see Figure 9).
According to [28], where both of these models are tested, the maximal error between them does not exceed 0.5 % for $h/R_2 < 0.2$ (see Figure 9). This means that the less complex parallel-plate model can be utilized which has been done in other literature [26, 29]. In the parallel-plate model $w$ is the mean circumference of the annular flow and can be written as $w = \pi (R_1 + R_2)$ and $h$ is the distance between the plates and can be written as $h = R_2 - R_1$. For a Bingham fluid the pressure gradient can be written as a quintic equation [30] that does not have an analytical solution but can, according to [28], be reduced to

$$P(T, V) = 1 + 2.07T - V + \frac{T}{1 + 0.4T},$$  \hspace{1cm} (2)

under the assumption that $0 < T < 1000$ and $-0.5 < V < 0$ where $P$ is the dimensionless pressure gradient, $T$ is the dimensionless yield stress and $V$ is the dimensionless piston velocity and are defined as

$$P = -\frac{wh^3}{12Apv_{0}\mu} \frac{dp}{dx},$$ \hspace{1cm} (3)

$$T = \frac{wh^2\tau_0}{12Apv_{0}\mu},$$ \hspace{1cm} (4)

and

$$V = -\frac{wh}{2Ap},$$ \hspace{1cm} (5)
where $A_p$ is the cross sectional area of the piston head and $v_0$ is the velocity of the piston head. From this result the authors of [28] could determine the dampers resistance force $F_t$ as a sum of the controllable force $F_\tau$ due to the generated yield stress $\tau_0$, the uncontrollable force $F_{uc}$ that consist of the viscous forces $F_\mu$ and frictional forces $F_f$. It is the ratio between the total resistance force $F_t$ and the uncontrollable force $F_{uc}$ that gives an indication of the dampers performance. According to [28] these forces are defined as

\begin{equation}
F_t = F_\tau + F_\mu + F_f,
\end{equation}

\begin{equation}
F_\mu = \left( 1 + \frac{whv_0}{2Q} \right) \frac{12\mu QLA_p}{wh^3}
\end{equation}

and

\begin{equation}
F_\tau = c\frac{\tau_0 LA_p}{h} \text{sgn} v_0
\end{equation}

where the constant $c = 2.07 + 1/(1 + 0.4T)$ in the interval $[2.07, 3.07]$ [29].

4.3 The equivalent quarter car model

This chapter examines the regenerative MR damper when applied to a quarter car model. The model is based on a mass-spring system created to simulate the working principal of a suspension system for a vehicle when exposed to a vertical acceleration caused by road irregularities. Figure 10 shows an example of a quarter car mass-spring system with two degrees of freedom.

![Equivalent quarter car model with two degrees of freedom](image)

The quarter car model is obtained by individually decomposing the component parts from the linear, mass-spring system, solving them and adding them together in order to get an accurate description of the combined system. This generates the governing differential equations describing the force balance for the mass-spring system. These can be derived as

\begin{equation}
M\ddot{Z} + C\dot{Z} + KZ = F_{\text{road}},
\end{equation}

with $M$ being a matrix containing the involved masses, $C$ a matrix containing the damping coefficients, $K$ the stiffness matrix for the system and $F_{\text{road}}$ the input force from the road acting on the system.
The vector $\mathbf{Z}$ contain the degrees of freedom for the system. For the special case when an MR damper is applied to the mass-spring system the parameter $C_i \mathbf{Z}$ in Equation (9) is substituted in order to compensate for the specific damping capability of the MR damper. From Chapter 4.2 it was concluded that the damping force that the MR damper could obtain was equal to the function given by Equation (6). With MR damper systems applied to a given mass-spring system the Equation (9) can be rewritten as

$$\mathbf{M} \ddot{\mathbf{Z}} + \mathbf{F} + \mathbf{KZ} = \mathbf{F}_{\text{road}},$$

with $\mathbf{F}$ being the vector describing the damping forces generated by the installed MR damping systems. When looking at the model described by Figure 10, with a single MR damper applied, the vector $\mathbf{F}$ is given by

$$\mathbf{F} = \begin{bmatrix} F_t \\ -F_t \end{bmatrix},$$

where $F_t$ is the damping force obtained from the function given by Equation (6). A relationship between the input force, $F_{\text{road}}$, and the displacements, $\mathbf{Z}$, can be obtained from solving the differential equation given by Equation (10). This relationship is interesting to study because it shows the amount of displacement that is generated by having a given input force. More importantly; it implicitly shows how much displacement is generated by having a given damper system; such as an MR damper.

The road profile generates the displacement $Z_r$ (see Figure 10) and can be obtained in several different ways. One method is to simply measure displacement $Z_r$ and then, by using a PSD [32], transform this data from the time domain to the frequency domain. This allows for the measured data to be analysed in the frequency spectrum and thereby allows for an analysis of the behaviour, at different frequencies, of the input force from the road acting on the system. Another method of obtaining input data for the road profile is by generating random data with the help of, for example, Matlab. According to [7] the road profile data can also be obtained by solving the differential equation

$$\ddot{q}(t) + 2\pi f_0 q(t) = 2\pi n_0 \sqrt{G_q(n_0)} v(t) w(t).$$

The parameter $G_q(n_0)$ is the roughness coefficient for the road and is chosen based on the category of the road (see Table 1).

<table>
<thead>
<tr>
<th>Road class</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_q(n_0) \cdot 10^{-6}$</td>
<td>16</td>
<td>64</td>
<td>256</td>
<td>1024</td>
<td>4096</td>
<td>16384</td>
<td>65536</td>
<td>262144</td>
</tr>
</tbody>
</table>

### 4.4 The linear energy harvester

The proposed regenerative MR damper utilizes a linear energy harvester as an electromagnetic transducer to salvage energy from the working suspension. The physical principles upon which the linear regenerative system is described is based on Faraday’s law of electromagnetic induction. When the magnets and coils start to move relative to each other a change in magnetic flux, $\phi$, appears. Faraday’s law states that the induced electromotive force (EMF), $\varepsilon$, is proportional to the rate of change of the magnetic flux. The direction of the induced EMF is given by Lenz’s law. Together these laws describes the relationship

$$\varepsilon = -N \frac{d\phi}{dt},$$

where $N$ is the number of turns the coil makes around the magnets [33]. When looking at the case with a moving conductor, such as this one, the electromotive force can be described by

$$\varepsilon = \int (\vec{v} \times \vec{B}) \cdot d\vec{r},$$

where $\vec{v}$ is the velocity of the conductor and $\vec{B}$ is the magnetic field.
when looking at a closed conducting loop. Here \( \vec{v} \) is the velocity of the moving conductor which in the case for the regenerative damper is caused by the vibration of the suspension. The magnetic field flowing through the magnets is given by \( \vec{B} \) and the length of the conductor is \( \vec{l} \). Note that Equations (13)-(14) are equivalent and that they are describing the induced EMF. For the specific case when the length of the conductor, the velocity of the conductor and the uniform magnetic field are mutually perpendicular; the EMF may be described by

\[
\varepsilon = vBL.
\]  

(15)

As described by Zuo et. al. [16]; the maximum current, \( I \), generated by the linear energy harvester, is given by the relationship

\[
I = \frac{\varepsilon}{R} = \sigma B_r v_z A_w,
\]

(16)

where \( R \) denotes the resistance in the circuit, \( \sigma \) the electrical conductivity of the given conductor, \( B_r \) the magnetic field intensity in the radial direction of the conductor, \( v_z \) the relative constant velocity of the coil conductor in the axial direction moving in the magnetic field and \( A_w \) the cross-sectional area of the conductor. The generated power, \( P \), can then be described as

\[
P = \varepsilon I = B_r^2 v_z^2 \sigma l A_w,
\]

(17)

with the conductor length \( l \). From equation (17) it is shown that a doubled increase of the magnetic field, which can be obtained by having stronger magnets, generates a quadratic increase in output power. This indicates the importance of having the right permeable materials and sufficiently strong magnets, so that a strong magnetic field can be obtained. The same relationship can be seen between the power and the velocity.
5 Sustainability

The environmental performance of a product can be divided into three categories; low global impact, low regional or local impact and resource efficiency. Low global impact refers to the products net contribution of carbon dioxide, low regional or local impact refers to leakage, pass-by noise and exhaust emission, and resource efficiency refers to choice of material, choice of fuel and its end of life treatment. Being one of the largest environmental hazards the vehicle industry is in need of increasing the efficiency of energy use which leads to the question of whether or not the regenerative MR damper is environmentally friendly.

The MR damper is able to make use of energy that otherwise would be wasted which would increase the environmental performance of vehicles when regarding low global impact. Having such a system implemented in the vehicles we use today can effectively contribute to making the cars and trucks more environmental friendly and thereby lessen their carbon footprint. The energy that can be harvested from the regenerative MR damper could be used to make the suspension system self-powered. The harvested energy could also be used as stored electrical energy in the battery which can be at the disposal for other systems. This means that the engine would not be needed to charge the battery on its own and could therefore use this extra energy to drive the vehicle. Having a regenerative MR system would therefore be beneficial for the decreasing of fuel consumption in vehicles and thus also in decreasing the global impact.

Because the MR damper utilizes an MR fluid as shock absorbent in the damper system there is a risk for leakage of this fluid. As stated by Flinn Scientific inc. [34] the MR fluid is classified as a non-hazardous material and has therefore small negative effect on the environment if leaked. Considering this fact and the fact that using the regenerative MR damper also decreases exhaust emissions and does not have any considerable effect on noise amplification in regard to other used systems, the system has no regional or local impact on the environment what so ever.

Finally, the regenerative MR damper has a relatively high resource efficiency due to it being easily recycled, not demanding any fuel and is composed of non-hazardous materials. Since the iron in the MR fluid can be separated out of the carrier liquid, it can be treated the same in a recycling process as motor oil [35]. Furthermore, the MR fluid does not have any negative impact on the ozone, as no Chlorofluorocarbons (CFC) are used when creating the liquid.

Because the regenerative MR damper is showing excellent environmental performance it can be concluded that this system is sustainable and has an overall positive impact on the environment.
6 Conclusion

This work investigated the application of regenerative suspension systems in vehicles. A briefing of earlier literature comprising regenerative damping was carried out. Further investigation of the electromagnetic regenerative damping technology was made by comparing five different technological solutions. Theoretical analysis of the regenerative MR damper was conducted and the aspect of environmental sustainability was reviewed.

From the literature review it could be concluded that the energy harvesters that utilized electromagnetic generators were the feasible option due to its promising development in the field of regenerative damping. Of the five compared electromagnetic energy harvesting models the regenerative MR damper was chosen for further analysis. Even though the MR damper was associated with bigger size and larger expenses, compared to the competing systems, it was concluded to be the best choice due to its high efficiency. The MR damper showed dominating damping capability, high reliability and robustness as well as promising energy regeneration potential. Furthermore, the linear electromagnetic energy harvesting system used in the MR damper was shown to be capable of powering the damper, thus making the regenerative MR damper a self-powered system.

The report describes the physical properties of the MR fluid, which is providing the damping capability in the MR system, with the quasi-static Bingham model. As mentioned in the report, when using the quasi-static model three assumptions are made which limits its range of use but is, despite this, viable when analyzing it for applications in a vehicle. The assumption that the MR fluid will act as a Bingham fluid is utilized because it takes into account the characteristics of the MR fluid when affected by a magnetic flux. The model for the pressure gradient limits the model regarding the yield stress and the piston velocity but not to an extent that will affect its viability when looking at a vehicle suspension system.

The environment in which the regenerative MR damper is applied was described using the quarter car model. This model was chosen to be presented because it provides for an efficient and compact way of describing the vehicle dynamics when excited by vertical displacement. Because the mass-spring system is linear it can easily be solved by obtaining the differential equations generated by superimposing the individual components of the mass-spring system. Furthermore, the model can easily be analyzed in Matlab, which is beneficial when studying simulations. Using this model, however, limits the descriptive range of the vehicles dynamics by being linear. This makes the model inaccurate if nonlinear dynamics comes into play. Because it is assumed that the tires of the vehicle is constantly in contact with the ground, another limitation would be exceeded if a detachment of the tire, from the ground, would occur. This example would result in a behavior of the system which cannot sufficiently be described by the proposed model.

The regenerative MR damper was examined from an environmental point of view by rating its degree of sustainability. This was done by looking at the environmental impact from three different angles – namely, on a local scale, a global scale and by examining the resource efficiency of the damper. It was shown that the regenerative MR damper had excellent environmental performance in all categories, making it highly sustainable. The regenerative MR damper was demonstrated to have an overall positive impact on the environment and therefore also on our society and the further development of sustainable technological solutions.

The aim of the report was to investigate whether or not a regenerative suspension system for improvement of energy consumption in vehicles was possible and it can now be concluded that it is. The regenerative MR damper showed promising results regarding both energy regeneration and damping performance. An average passenger vehicle dissipates around 200 W and the regenerative MR damper was shown to regenerate up to 90 W which means that a considerable amount of this, otherwise
wasted, energy can be utilized. This system can therefore maintain good ride comfort with the help of the MR damper and reduce the vehicles environmental impact making the system highly desirable for future implementation.
7 References


