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# Semi-active suspension systems using magneto-rheological fluids

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# Summary

For a given vehicle, the suspension system isolates the passengers and payload from shock and vibration. In addition, the system also enables the wheels to maintain contact with the surface, thereby affecting stability and control of the vehicle. The challenge in designing a (traditional) passive suspension system is the conflicting criteria of road holding, payload and passenger comfort. This means that a passive suspension system either has harsh ride characteristics, but good control characteristics, or vice versa. Typically, the type of system used is largely determined by the intended usage of the designed vehicle. Semi-active suspension systems, and in particular active suspension systems (both characterised as controllable suspension systems), are considered to be a way of achieving both excellent ride and handling characteristics, and both systems are capable of varying its parameters actively whilst the vehicle is in motion. A semi-active suspension system is a good compromise between a passive and an active suspension system, and such a system has in principle no additional energy demand.

Regarding semi-active suspension systems, a couple of different technical solutions (i.e. principles) exist. Semi-active suspension systems using magneto-rheological (MR) fluids are perhaps the most promising technology among this group of systems. Such fluids are characterised as controllable fluids, and are manufactured by suspending ferromagnetic particles in a carrier fluid. MR fluids (MRF) exhibit a change in rheological properties (including the viscosity) when being exposed to a magnetic field. The viscosity changes can be controlled accurately by varying the magnetic field strength, giving MR fluids the ability to reversibly change from viscous liquids to semi-solids in milliseconds. This gives a rapid response interface between electronic controls and mechanical systems, making MRF technologies attractive for many applications (e.g. dampers). Semi-active suspension systems using MR fluids have among other successfully been installed in luxury automobiles, sports cars, light trucks and sport utility vehicles. In addition, some research projects exist where such systems have been integrated in military vehicles (e.g. Stryker and HMMWV).

Controllable suspension systems, including semi-active systems, can greatly improve the performance of a military vehicle. Such systems can clearly have a positive impact on health and comfort factors for occupants in such a vehicle. This is due to reduced vibrations in critical frequency ranges. A controllable suspension system can also improve the tactical mobility of a vehicle, since a reduction in absorbed power is experienced for a given velocity. Increased mobility can also increase the survivability. Controllable suspension systems can also give additional benefits, e.g. increased hit probability (i.e. the enemy), increased payload, increased durability of the vehicle, increased operational range and more consistent driving characteristics. Unfortunately, a controllable suspension system integrated into a military vehicle will add complexity to the vehicle, that is, compared to a conventional (passive) suspension system. This could have a significant impact on maintenance needs. Another current disadvantage with controllable suspension systems is that, up to now, only research projects exist, leading to a lack of field experience.

# Sammendrag

Et kjøretøys fjæringssystem isolerer passasjerene, og eventuell nyttelast, fra sjokk og vibrasjoner. Et slikt system medfører at hjulene kan opprettholde kontakten med underlaget, og påvirker dermed kjøretøyets stabilitets- og kontrollegenskaper. Hovedutfordringen med å designe et tradisjonelt fjæringssystem (dvs. passivt) er avveiningene mellom kjøreegenskaper, nyttelast og passasjerkomfort. Et passivt fjæringssystem har dermed enten gode kjøreegenskaper og dårlig passasjerkomfort, eller motsatt. Valg av system bestemmes stort sett ut fra kjøretøyets bruksområde. Man kan derimot, ved å benytte regulerbare fjæringssystem (semiaktive eller aktive), oppnå både gode kjøreegenskaper og god passasjerkomfort. Slike systemer gir en muligheten til å endre fjæringsparametre fortløpende mens kjøretøyet er i bevegelse. Et semiaktivt fjæringssystem er et godt kompromiss mellom et passivt og et aktivt system, og har i prinsippet et neglisjerbart energibehov.

Flere alternative tekniske løsninger eksisterer for semiaktive fjæringssystem. En av de mest lovende blant disse er systemer som benytter magnetoreologiske (MR) væsker; karakterisert som kontrollerbare væsker. De blir produsert ved å introdusere ferromagnetiske partikler i en bærervæske. Dersom man påtrykker et magnetisk felt på en MR væske, vil det oppstå en endring i væskas reologiske egenskaper, deriblant viskositeten. Viskositetsendringene kan kontrolleres nøyaktig ved å regulere den magnetiske feltstyrken. Dette medfører at en slik væske kan endre tilstand fra viskøs væske til et halvmassivt legeme i løpet av millisekunder. Dermed kan man oppnå svært hurtig respons i det mekaniske systemet gjennom elektronisk styring. Dette har ført til at teknologier som benytter MR væsker er attraktive innenfor mange bruksområder, for eksempel i dempere. Semiaktive fjæringssystemer som benytter MR væsker har med stort hell blitt installert i luksusbiler, sportsbiler og lette lastebiler. Det finnes også enkelte forskningsprosjekter hvor slike systemer har blitt integrert i militære kjøretøy (Stryker og HMMWV).

Regulerbare fjæringssystem, herunder semiaktive systemer, kan helt klart øke ytelsen til militære kjøretøy. Slike systemer kan ha en meget positiv effekt på faktorer knyttet til helse og komfort for personer som oppholder seg i slike kjøretøy. Dette skyldes reduserte vibrasjoner innenfor det kritiske frekvensområdet. Regulerbare fjæringssystemer kan også forbedre et kjøretøys taktiske mobilitet, da man oppnår en reduksjon i absorbert effekt for en gitt hastighet. Økt mobilitet kan også forbedre overlevelsesevnen (survivability). Samtidig vil kjøretøyet kunne ta en vesentlig større nyttelast. Regulerbare fjæringssystemer kan også gi øvrige fordeler, for eksempel økt treffsannsynlighet (mot fienden), økt levetid, økt operasjonsrekkevidde og jevnere kjøreegenskaper. Sammenliknet med et tradisjonelt fjæringssystem vil et regulerbart fjæringssystem integrert i et militært kjøretøy øke kjøretøyskompleksiteten. Dette kan gi store konsekvenser for vedlikeholdsbehovet. En annen ulempe per dags dato er at slike systemer er helt uten stridserfaring, da kun forskningsprosjekter har vært gjennomført. Disse testene har dog vært gjennomført på svært tøffe og vanskelige testbaner.

# Contents

# Preface

This work is related to a NIAG (NATO Industry Advisory Group) study on active suspension systems for military vehicles (sub-group 116). The objective of this study is to examine the contribution that active (and semi-active) suspension systems can provide to the performance of military vehicles, both wheeled and tracked, in terms of mobility, payload, volume, protection and lethality. Another part of the study is to identify active (and semi-active) suspension technologies that can contribute to the military vehicle requirements in the near and longer term time frames, based on technology readiness levels. In addition, performance benefits, limitations and trade-offs for the different types of systems shall be addressed.

The final NIAG report on active suspension systems (to be published in late 2008) will contain a small extract of the information given in this report.

# 1 Introduction

This report is related to FFI-project number 1019, TEKNISK[1], where the objective is to evaluate, and in some cases test and demonstrate, evolving technologies for future ground combat vehicles. The four main areas of interest are survivability, lethality, mobility and $C^2$IS, and this report focuses primarily on mobility. Another important activity within the project is to assist the Norwegian army in current acquisition projects. This involves acquisition of different kinds of vehicles, with belonging weapon systems (e.g. remote weapon stations).

A conventional (passive) suspension system has always been designed as a compromise. No such system can both provide a comfortable ride and optimal handling. Semi-active suspension systems, and in particular active suspension systems[2], are considered to be a way of increasing the freedom to specify independently the characteristics of the payload, handling and ride quality. This means that particularly active suspension systems are capable of providing both excellent ride and excellent handling. A semi-active suspension system is a good compromise between a passive and an active suspension system. A semi-active system has the ability to vary its parameters in order to achieve a certain level of compromise between road holding, payload and comfort, whilst the vehicle is in motion.

For a semi-active suspension system, a couple of different technical solutions (i.e. principles) exist. This includes solutions based on controllable fluids (magneto-rheological and electro-rheological), hydraulics, compressible fluids and friction based systems. Semi-active suspension systems using magneto-rheological (MR) fluids are perhaps the most promising technology among this group of systems. MR fluids (MRF) are characterised as controllable fluids that are manufactured by suspending ferromagnetic particles in a carrier fluid. They are called controllable fluids since they exhibit a change in rheological properties (can among others affect the viscosity) when being exposed to a magnetic field. Due to this, MR fluids have the ability to reversibly change from viscous liquids to semi-solids in milliseconds when being exposed to a magnetic field. This gives a rapid response interface between electronic controls and mechanical systems, making MRF technologies attractive for many applications (e.g. dampers). Semi-active suspension systems using MR fluids have among others successfully been installed in some upper class cars. Up to now, a few research projects exist where such systems have been integrated into a military vehicle.

From a military point of view, controllable suspension systems (including semi-active systems) offer a lot of opportunities that can improve the performance of a military vehicle. This includes a reduction in the vibration of the vehicle structure, which affects several areas. Tests have shown that it is possible to reduce the absorbed power for a given velocity. This means that it is possible

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[1] Teknologier for nettverksintegrert stridskjøretøy

[2] Semi-active and active suspension systems are defined as controllable suspension systems. Both systems parameters may be varied actively to achieve a certain level of compromise between road holding, payload and comfort, whilst the vehicle is in motion (see section 2.2).

to have a higher velocity over a given terrain. Other advantages include reduced fatigue loading of vehicle structure and payload, improved vehicle stability and handling characteristics and improved accuracy during surveillance, targeting and weapons firing. Some disadvantages also exist, mostly related to cost, system complexity and maintenance.

This report is on controllable suspension systems, with special emphasis on semi-active suspension systems using MR fluids. Chapter 2 gives a brief introduction to vehicle suspension systems, whereas chapter 3 points out potential benefits by using a controllable suspension system. Chapter 4 is concerned with MR fluids, including introduction, rheological background and different operational modes. Chapter 5 focuses on applications of MR fluids in semi-active suspension systems. This includes a section describing MR fluid technology in military vehicles. Some concluding remarks are given in chapter 6.

# 2 Suspension systems

## 2.1 The function of the suspension system

For a given vehicle, the suspension system isolates the passengers and payload from shock and vibration induced by the road surface. This isolation also improves the lifetime and durability of the vehicle. However, the suspension system also enables the wheels to maintain contact with the road, thereby affecting stability and control of the vehicle. A suspension system comprises three crucial elements:

- ✓ Flexibility, which is provided by a spring that distorts and recovers as the wheel traverses disturbances in the road surface
- ✓ Damping – Essential to restrain the body and wheel from resonant motions
- ✓ Location of wheel and axle

Generally, good ride comfort requires a soft suspension (i.e. soft springs), whereas insensitivity to applied load requires stiff suspension (i.e. stiff springs). On the other hand, good handling requires a suspension setting somewhere between the two. In a traditional suspension design (i.e. passive system), a trade-off exists between the three conflicting criteria of road holding, payload and passenger comfort. Typically, the type of system used (soft vs. stiff) is largely determined by the intended usage of the designed vehicle.

A passive suspension system usually consists of a spring and a damper. The ride quality level is often determined by the amount of energy dissipation by the damper per cycle and the amount of energy stored and released by the spring. Uncomfortable ride is typically caused by a large amount of energy dissipation, although it is beneficial for off-road driving. Semi-active suspension systems, and in particular active suspension systems, are considered to be a way of increasing the freedom to specify independently the characteristics of the payload, handling and ride quality. Figure 2.1 points out the differences between an active and a passive suspension system. In addition, the figure illustrates some terms defined in section 2.2.

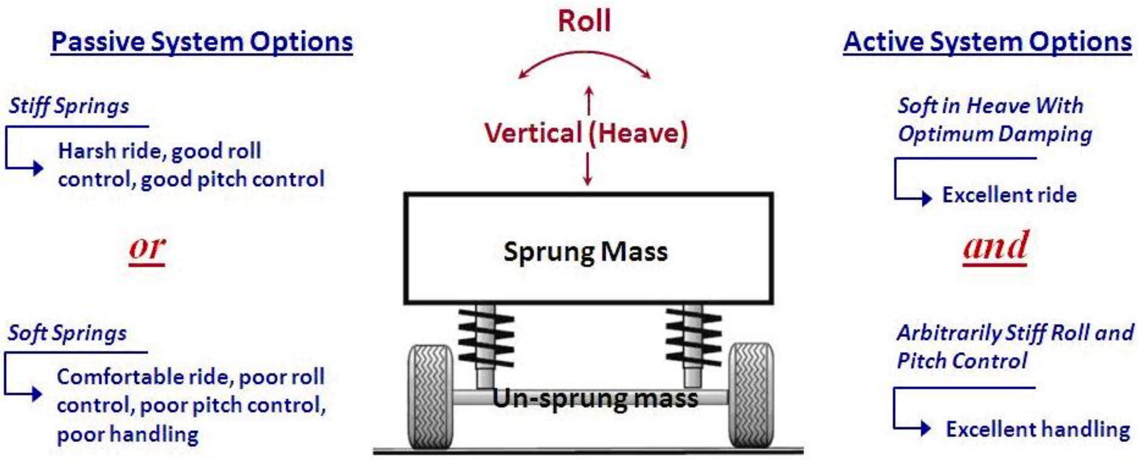

*Figure 2.1 – Active vs. passive suspension systems [1]*

## 2.2 Terms and definitions

***A passive suspension system*** has the ability to store energy via a spring and to dissipate it via a damper. Its parameters are generally fixed, being chosen to achieve a certain level of compromise between road holding, payload and comfort. Height or load adjustment may be incorporated in a passive suspension system.

***A semi-active suspension system*** has, like the passive suspension system, the ability to store energy via a spring and to dissipate it via a damper. However, its parameters may be varied actively to achieve a certain level of compromise between road holding, load carrying and comfort, whilst the system is in motion. A semi-active system has no external energy requirement other than for control.

***An active suspension system*** has the ability to store, dissipate and to introduce dynamic energy to the system. It may vary its parameters upon operating conditions, whilst the system is in motion.

In a ***high bandwidth suspension system*** one generally considers an actuator connected between the sprung and the unsprung masses of the vehicle. Such a system aims to control the suspension over the full bandwidth (i.e. full frequency range) of the system. In particular, this means improvement of the suspension response around resonant frequencies[3] of the system. This system will consume a significant amount of energy and will require actuators with a relatively wide bandwidth.

***Low bandwidth systems*** are also known as slow-active or band-limited systems. In this class the actuator will be placed in series with a road spring and/or damper. A low bandwidth system aims

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[3] The terms rattle-space and tire-hop may be regarded as resonant frequencies of such a suspension system

to control the suspension over the lower frequency range (typically around the rattle-space frequency). At higher frequencies the actuator effectively locks-up and hence the wheel-hop motion is controlled passively. With these systems we can achieve a significant reduction in body roll and pitch during manoeuvres such as cornering and braking, with lower energy consumption than a high-bandwidth system.

A ***preview system*** aims to increase the bandwidth of a band-limited system by using feed-forward or knowledge of future road inputs. Some systems aim to measure road disturbances ahead of the vehicle, and then use both standard feedback control and feed-forward from the sensor to achieve a superior response. Others aim to use the information available from the front strut deflection to improve the performance of the rear suspension.

# 3 Potential benefits of using a controllable suspension system

## 3.1 Introduction

Controllable suspension systems (semi-active or active) have successfully been installed in some upper class cars (see section 5.1). In addition, some semi-active solutions have been installed by truck manufacturers. From a military point of view, controllable suspension systems offer a lot of opportunities that can improve the performance of a military vehicle. Up to now, only research projects exist, and some examples are given in section 5.5. This chapter briefly discusses how a controllable suspension system can improve certain key areas relevant for military vehicles.

## 3.2 Human factors

Human factors are crucial for design and use of military vehicles, since the effect of vehicle ride discomfort strongly influences a person’s ability to carry out different assignments. This includes both on-board tasks (e.g. driving, observation, communication, computation and firing on the move) and tasks after the transport (e.g. fighting). The key question is to what degree prolonged ride discomfort degrades the ability to carry out tasks.

Military vehicles shall through human engineering design provide work environments that minimise factors (including vibration, acceleration, shock, blast and impact forces) degrading human performance or increase error. Uncontrolled variability in these factors must be kept within safe limits. Vibration is classified as a physical hygiene hazard in a workplace (e.g. military vehicle). It is separated into two sub-categories, where Whole-Body Vibration (WBV) is experienced when the operator, driver or passengers sits on or in any kind of a vibrating vehicle. Human exposure to periodic, random and transient mechanical vibration can interfere with comfort, activities and health.

Vibration is often complex, contains many frequencies, occurs in several directions and changes over time, and the effects may be manifold. The health effects vary considerably from situation to situation when being exposed to WBV. Generally, vertical vibrations, which seem to be most uncomfortable, fall in the frequency ranges of 4 – 8 Hz (WBV) and 18 – 200 Hz (vibration of individual body parts). It is also well known that very low frequencies (below 1 Hz) can cause dizziness and motion sickness. Based on this, it should be clear that vehicle suspension systems should minimise vibrations in the critical frequency ranges indicated. A seated human is most sensitive to vertical vibrations between 4 and 8 Hz. For an equivalent sensation of intensity outside this range, greater amplitude (i.e. rms acceleration) is required. U.S. Army and NATO usually define ride quality in terms of absorbed power (in watts), which can be calculated from measured accelerations. It is generally accepted that 6 watts is the upper limit at which a person can operate for an eight hour day.

Although vertical vibration is a dominant factor regarding health and endurance aspects, horizontal and rotational vibration can be important as well. This is particularly true for high vehicles, where pitch and roll motions can cause significant longitudinal and lateral inputs to the heads of the occupants. Studies have shown that "pure" roll motion causes greater discomfort than "pure" pitch motion, which in turn causes more discomfort than "pure" yaw motion. At high frequencies, the rotational accelerations are high and will usually be encountered with translational accelerations. The latter, if occurring vertically, can often be a greater source of discomfort than the rotational vibration. "Pure" rotational vibration can clearly interfere with human activity. Such movements can degrade vision (temporary), disturb "limb" movements, result in fatigue and contribute to motion sickness symptoms.

### 3.3 Mobility

Cross-country performance of military off-road vehicles is crucial in military operations. Such performance can be determined by using different methods. Maximum velocity and harshness of pitch and roll motions of vehicles under off-road conditions are examples of parameters that can be used in order to determine the cross-country performance. As a consequence, the suspension system of military off-road vehicles is closely related to the cross-country performance characteristics on rough terrain.

Only tactical mobility is considered in this section. It is here defined as a vehicle's ability to move within the battle-field and the ability to navigate through rough terrain. It is comprised of the following parameters:

- ✓ On/off road speed
- ✓ Maximum speed
- ✓ Acceleration
- ✓ Maximum gradient
- ✓ Maximum side slope
- ✓ Vertical obstacle
- ✓ Ground clearance
- ✓ Angle of approach and departure
- ✓ Trench cross ability
- ✓ Turning circle diameter

- ✓ Speed in water
- ✓ Deep fording speed
- ✓ Operating range

If a controllable suspension system is installed on either a wheeled or tracked military vehicle, the vehicle's speed parameters and acceleration would be increased. In addition, if it is possible to control the effect of the suspension system per wheel independently, several terrain dependent parameters could be improved (e.g. maximum gradient, maximum slide slope, vertical obstacle, ground clearance etc). So it is clear that it is possible to improve the tactical mobility of a military vehicle with a controllable suspension system.

## 3.4 Probability of hit

It is obvious that a weapon system that is stabilised has a higher probability of hit (i.e. the enemy) than an unstabilised one. The probability of hit is a function of different parameters. This includes vertical and horizontal movements of the vehicle and gun stabilisation system limits. If a controllable suspension system is installed on either a wheeled or tracked military vehicle, a reduction in the movement of the weapon system can be accomplished. Such a reduction will most likely lead to an increased probability of hit.

## 3.5 Survivability

According to the onion diagram in Figure 3.1, survivability consists of several layers. Some of these can be influenced by a controllable suspension system.

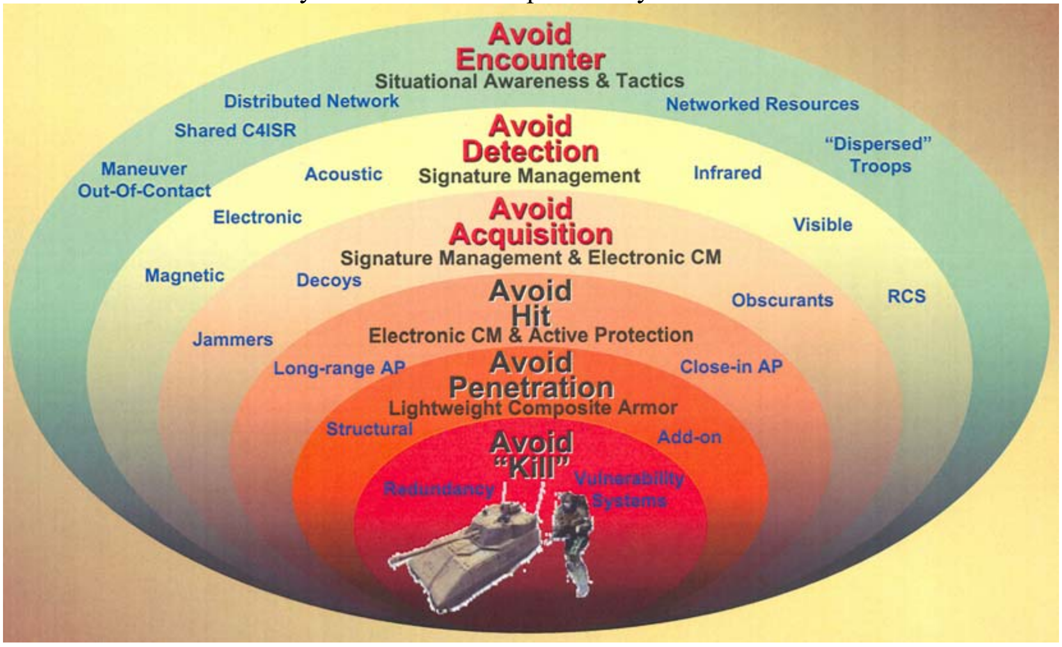

*Figure 3.1 – Survivability: Onion diagram [2]*

An increased mobility makes it easier for the vehicle to avoid encounter (e.g. manoeuvre out-of-contact). In addition, the ability to move faster over rough terrain can also contribute to avoiding being hit. A controllable suspension system will also protect better against shock and vibration, which is important for subsystems such as electronics and optics.

### 3.6 Other factors

A controllable suspension system can also give additional benefits. This includes an increased payload, among others due to reduced stress on the vehicle structure. A military vehicle equipped with such a system can also experience an increased durability and reliability. This is due to reduced stress on the vehicle structure, less shocks and less accidents (due to better handling). In addition, an increased operational range of the vehicle can be obtained. This is among others due to less roll resistance. At the same time, the vehicle will experience more consistent driving characteristics.

## 4 Magneto-rheological (MR) fluids

### 4.1 Introduction to MR fluids

Magneto-rheological fluids can be characterised as controllable fluids. They are manufactured by suspending ferromagnetic particles in a carrier fluid. The latter is typically some kind of oil. MR fluids exhibit a change in rheological properties when being exposed to a magnetic field (this is known as the on-state). Rheology is defined as the study of the deformation and flow of matter (typically materials such as rubber, molten plastics, magneto-rheological fluids, blood, paint, etc) under the influence of an applied stress. The rheological properties of a liquid are the dominant features that can be quantified to characterise its behaviour. The properties that can be affected are elasticity, plasticity and viscosity. In the on-state, ferromagnetic particles are magnetically induced and aggregate to form chain-like or column-like structures parallel to the applied field. Due to this, MR fluids have the ability to reversibly change from viscous liquids to semi-solids in milliseconds when being exposed to a magnetic field. This feature enables a rapid response interface between electronic controls and mechanical systems, making MRF technologies attractive for many applications (e.g. dampers).

A typical MR fluid contains between 20 – 40 % by volume (50 % is maximum) of suspended particles. Normally, soft iron particles are used (e.g. carbonyl iron), since they provide a good trade-off between cost and fluid strength (i.e. large saturation magnetisation). Other particles that are used include powder iron or iron/cobalt alloys. The particle size is in the μ-meter range and varies according to different manufacturing processes. The particle size is varied in order to achieve different purposes (e.g. torque vs. viscosity). The particles are suspended in a carrier liquid, e.g. a mineral oil, synthetic oil, water or glycol. In addition, a variety of other additives (like those found in lubricants) are commonly added to the fluid. This is done in order to reduce gravitational settling, enhance particle suspension and lubricity, modify viscosity and reduce wear. Lord Corporation is the world’s leading provider of MR fluids, and Table 4.1 summarises certain properties related to three different fluids produced by this company. Table 4.2 gives an overview of some other MR key features.

*Table 4.1 – Properties of different MR fluids produced by Lord Corporation*

| | MRF-122EG | MRF-132DG | MRF-140CG |
|---|---|---|---|
| **Base fluid** | Hydrocarbon | Hydrocarbon | Hydrocarbon |
| **Compatibilty** | | | |
| Buna N (Nitrile) | Good | Good | Good |
| Butyl | Poor | Poor | Poor |
| EDPM/EDR | Poor | Poor | Poor |
| Fluorelastomer | Good | Good | Good |
| Natural Rubber | Poor | Poor | Poor |
| Neoprene | Good | Good | Good |
| Silicone | Fair | Fair | Fair |
| Iron | Good | Good | Good |
| Stainless steel | Good | Good | Good |
| Aluminium | Good | Good | Good |
| Polyethane | Good | Good | Good |
| **Open/closed system** | Both | Both | Both |
| **Operating temperature [C]** | -40 to + 130 | -40 to + 130 | -40 to + 130 |
| **Flash point [C]** | > 150 | > 150 | > 150 |
| **Appearance** | Dark gray liquid | Dark gray liquid | Dark gray liquid |
| **Viscosity @ 40 C [Pas]** | 0.042 +/- 0.020 | 0.092 +/- 0.015 | 0.280 +/- 0.070 |
| **Solids content by weight [%]** | 72 | 81 | 85 |
| **Density [g/cm3]** | 2.28 - 2.48 | 2.98 - 3.18 | 3.54 - 3.74 |

*Table 4.2 – MRF key features [3]*

| Representative feature | Typical MR fluid |
|---|---|
| Maximum yield stress | 50 - 100 kPa |
| Power supply | 2 - 24 V at 1 - 2 A |
| Response time | Some millisecond |
| Operational field | Up to 250 kA/m |
| Energy density | 0.1 J/cm$^3$ |
| Stability | Good for most impurities |
| Operational temperature | -40 C up to 150 C |

Normally, MR fluids are free flowing liquids having almost the same rheological behaviour as the carrier fluid. However, one exception is that the metal powder content of the MR fluids makes the liquid slightly “thicker”. Without a magnetic field, a free flowing MR fluid can be illustrated as in Figure 4.1 (the off-state).

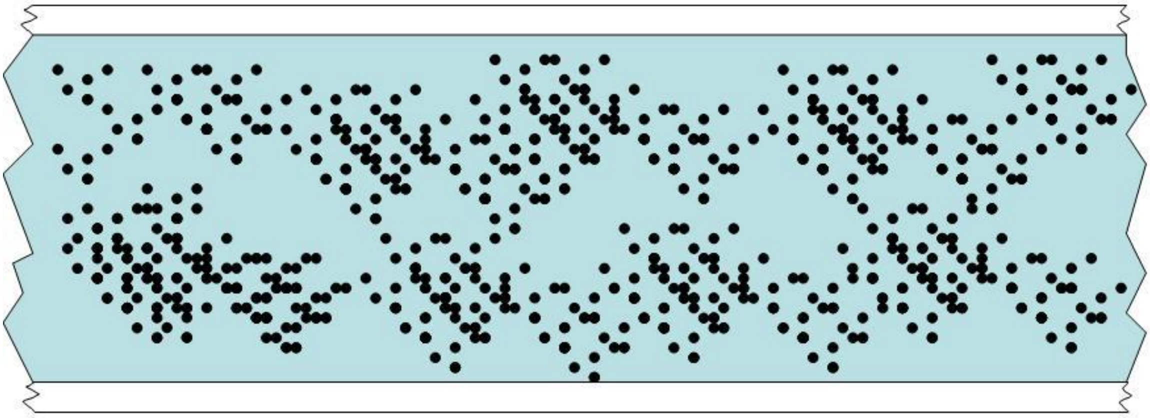

*Figure 4.1 – Free flowing MR fluid*

As seen in the figure above, under normal circumstances (without a magnetic field present) the magnetic (i.e. iron) particles are distributed randomly in the carrier fluid. In this state, the MR fluid behaves like the base fluid in accordance with the chemical compositions. However, if a magnetic field is applied to the fluid, the iron particles align themselves along the lines of the magnetic flux. As seen in Figure 4.2, a magnetic field causes the particles to form linear chains parallel to the field.

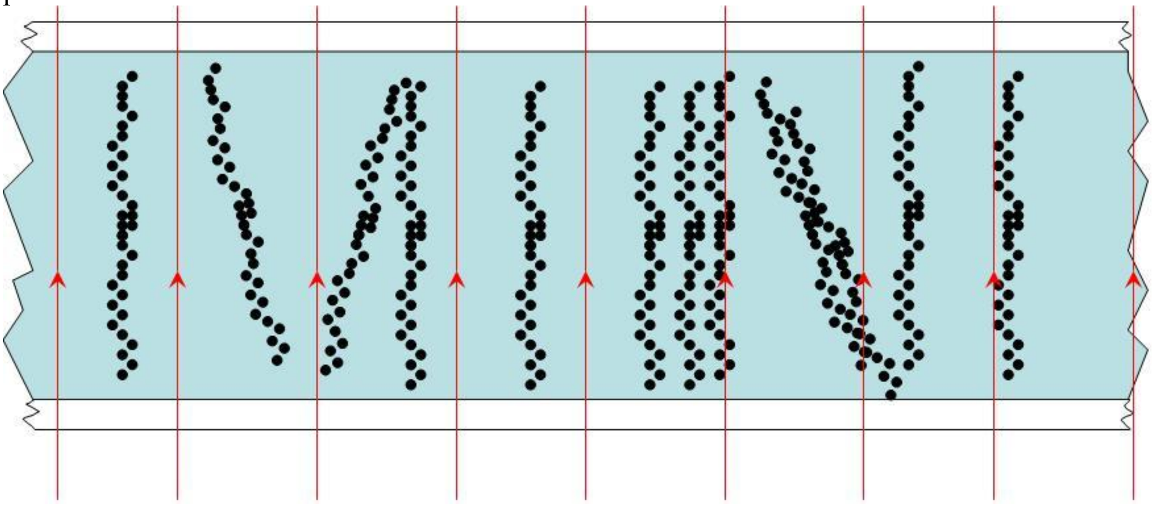

*Figure 4.2 – Magnetic field applied to an MR fluid*

The magnetic field is capable of solidifying the suspended iron particles, and thereby restricts the fluid movement. The metal particles are guided by the magnetic field to form a chain-like structure. These chains have a mechanical resistance to the fluid flow. As a consequence, the viscosity of the fluid increases. The viscosity changes can be controlled by the magnetic field strength. This makes it possible to change a free flowing liquid into some sort of semi-solid condition. Since the MR effect is reversible, the original condition of the liquid is re-established if the magnetic field is removed. Consequently, the strength of the magnetic field controls the level of the MR effect.

## 4.2 Rheological background

As discussed in section 4.1, an MR fluid is a fluid with rheological behaviour that depends on the strength of a magnetic field. Also, an MR fluid can reversibly change from liquid to semi-solid. Normally, the viscosity of a fluid changes with physical properties, such as chemical composition, shear stress and temperature. Unfortunately, these features are not easily controlled in most applications. They are most likely fixed by the operational environment in each setting. As an example, the variation of a fluid's viscosity with temperature is reversible, but this does not allow the viscosity to be controlled easily.

The dynamic viscosity (η) of a liquid is defined in equation (4.1) below (see [4]):

$$\eta = \frac{\tau}{\gamma^0} \tag{4.1}$$

Here, η is the dynamic viscosity [Pa s], τ is the shear stress [$N/mm^2$] and $\gamma^0$ is the shear rate [$s^{-1}$]. For a Newtonian fluid (like water), the viscosity does not change if the shear rate changes. This means that it is a linear relationship between the shear stress and the shear rate for such a fluid.

It is recognised that a simple Bingham visco-plasticity model is well suitable for describing the rheological behaviour of an MR fluid. A Bingham fluid is defined as an incompressible visco-plastic yield stress fluid. It is characterised by the fact that when the stress is below the yield stress, the strain rate is zero, and the fluid moves as a rigid solid (see Figure 4.3). When the stress is above the yield stress, the strain rate is in linear relationship with the stress, and consequently, the fluid flows in a viscous manner.

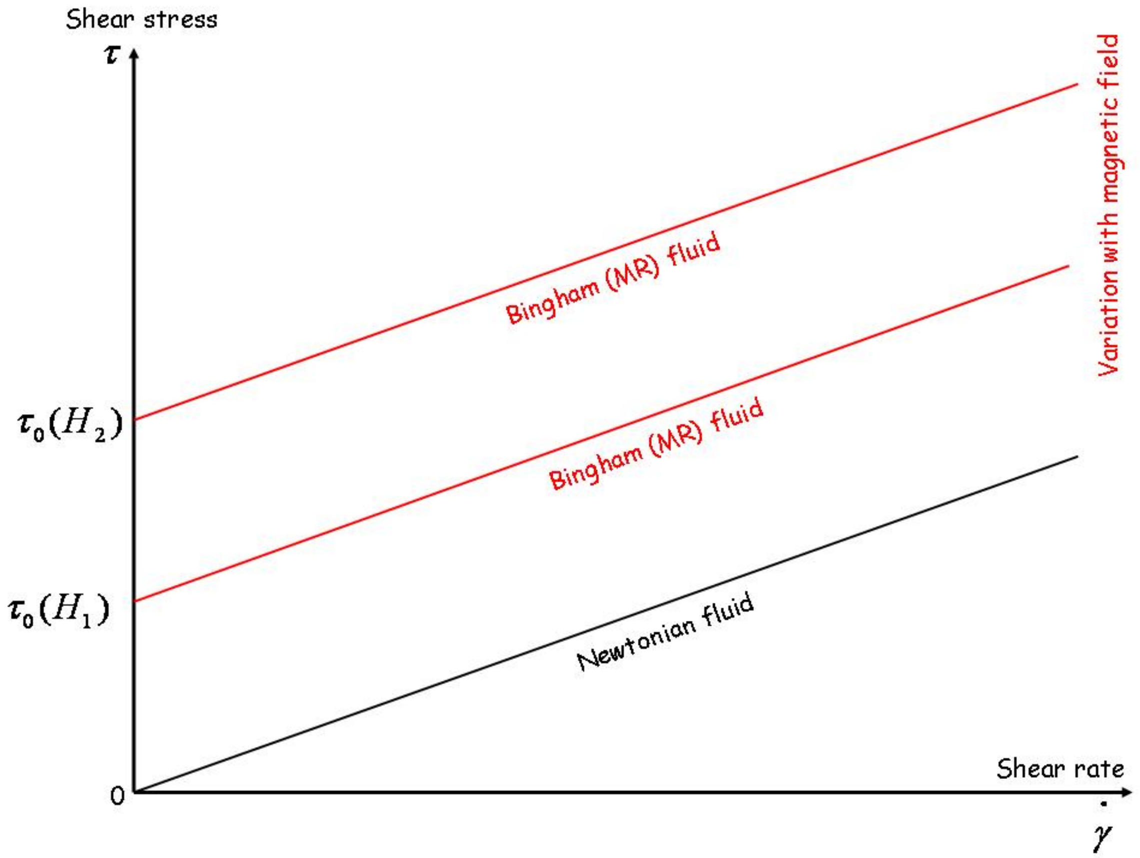

*Figure 4.3 – Shear stress vs. shear rate for Newtonian and Bingham (MR) fluids [3]*

As shown in the figure above, a typical relationship between shear stress and shear rate for a Bingham fluid is given. Figure 4.3 also compares the behaviour of a Newtonian fluid with a Bingham fluid. If a magnetic field is not present, an MR fluid behaves like a Newtonian fluid. Otherwise, the MR fluid behaves like a Bingham fluid. When a magnetic field is present, there is some resistance to flow at zero shear rate. The force causes therefore a plastic deformation, but no continuous movement. The maximum stress that can be applied without causing continuous movement is called the yield stress. For an MR fluid, the yield stress can be controlled by varying the magnetic field. The total shear stress (τ) is defined in equation (4.2) below (see [5]).

$$\tau = \tau_0(\mathrm{H}) + \eta \times \gamma^0 \qquad (4.2)$$

Here, $\tau_0(H)$ [Pa s] is the yield stress caused by the applied magnetic field, where H [A/m] is the magnetic field strength. The magnetic field required to impose the control depends especially on the quality and quantity of the metal powder. The strength of an MR fluid depends on the square of the saturation magnetisation of the suspended particles. Generally, saturation magnetisation is a measure of the maximum amount of field that can be generated by a material. It depends on the strength of the dipole moments of the atoms that make up the material and how densely they are packed together. This means that in order to have a strong MR fluid, particles with large saturation magnetisation must be chosen. Figure 4.4 gives an example of predicted yield stress as a function of magnetic field strength for several MR fluids available from Lord Corporation.

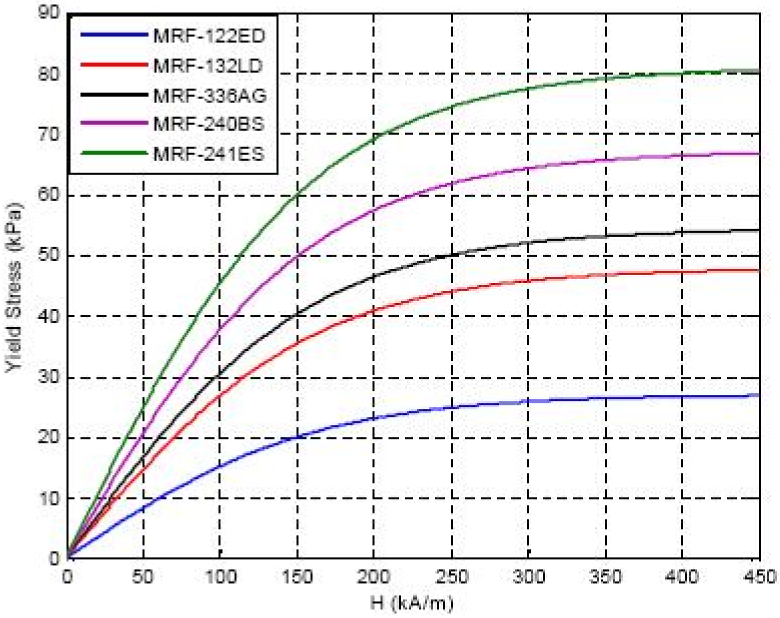

*Figure 4.4 – Yield stress vs. magnetic field strength [6]*

An alternative to the Bingham model is the Herschel-Bulkey model (see [5]). This model accounts for the post-yield shear thinning (or thickening) behaviour of MR fluids (deviation of the linear relationship shown in Figure 4.3).

It is a known fact that an MR fluid's response to a magnetic field occurs in a matter of milliseconds. Even so, the degree of response from the fluid does vary with the time spent in the presence of a magnetic field (defined as fluid dwell time [6]). This means that dwell time is the time it takes for the MR fluid to flow through the MR valve. So unless the fluid is stationary in the magnetic field part of e.g. a damper, it is not certain that the fluid will develop 100 % of its expected yield stress. As an example, Figure 4.5 shows dwell time vs. fluid velocity for two different valve lengths (25.4 mm and 6.35 mm). As shown in the figure, the dwell time varies between 12.4 ms and 0.18 ms depending on fluid velocity and valve length.

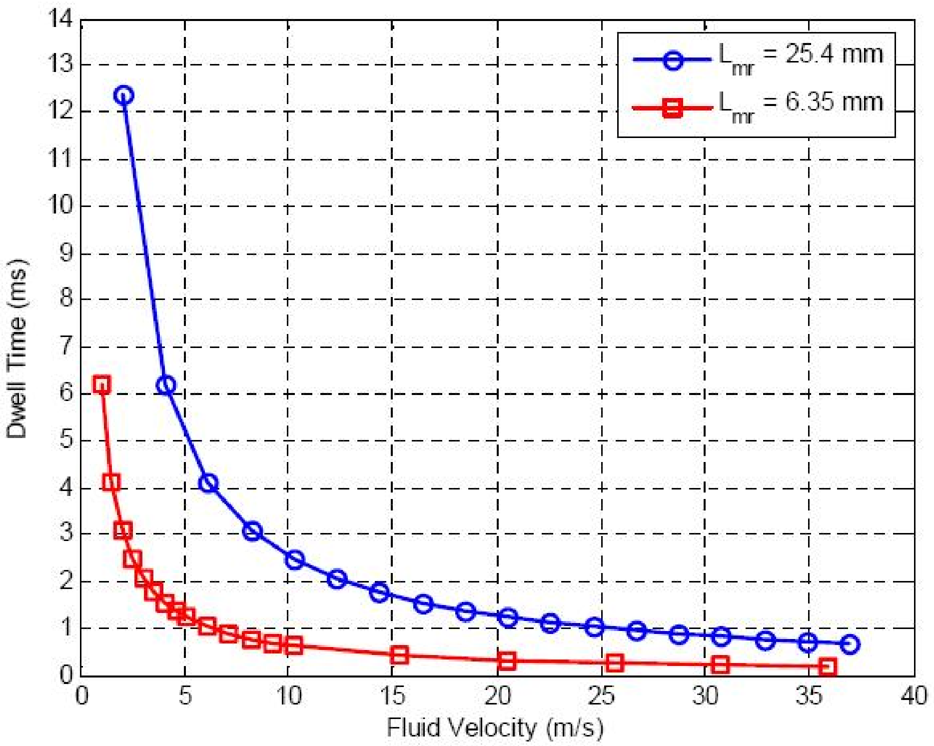

*Figure 4.5 – Dwell time for fluid through active valve length [6]*

More important is the yield stress dependence on the dwell time. Figure 4.6 shows how the yield stress increases with dwell time for two different valve lengths (25.4 mm (left) and 6.35 mm (right)). The magnetic field strength's impact on the yield stress is also shown in the figure.

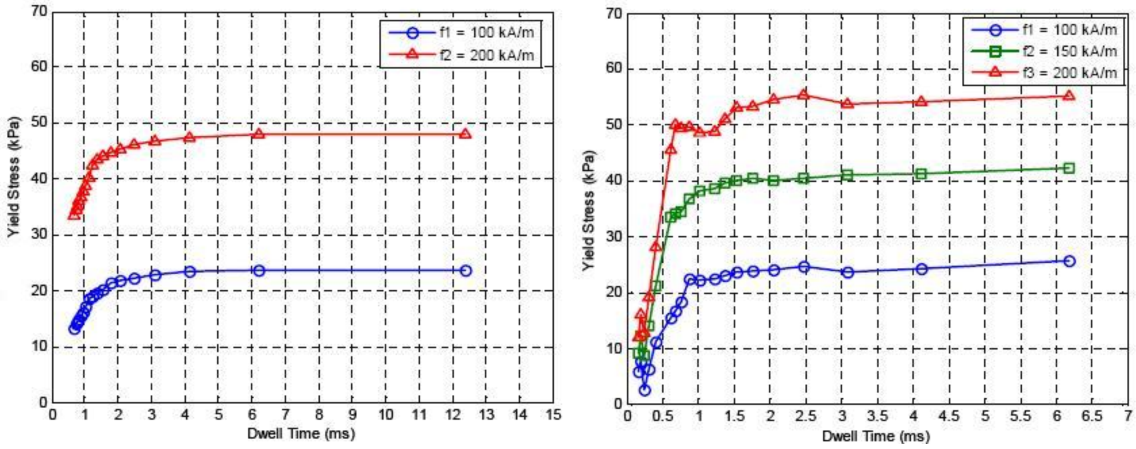

*Figure 4.6 – Yield stress as a function of dwell time for two different valve lengths [6]*

As shown in the figure above, for the 25.4 mm valve length, the yield stress remains relatively constant for dwell times greater than 2 ms. Similar results are observed for the 6.35 mm valve length for dwell times greater than 1 ms. So even though an MR fluid reacts within milliseconds, it is crucial that the fluid spends sufficient time under the influence of a magnetic field. This point is well illustrated in Figure 4.6, where the figure illustrates how important dwell time is for achieving full potential of the MR fluid.

## 4.3 MR fluid operational modes

All devices that use MR fluids can be classified as operating in one of the three modes demonstrated in Figure 4.7. As shown in the figure, valve mode involves fluid flowing as a result of a pressure gradient between two stationary plates. Devices that utilise this mode include servo-vales, dampers, shock absorbers and actuators. The pressure drop, ΔP, in an MR fluid device utilising the valve mode principle can be represented by the following equation (see [7]):

$$\Delta P = \Delta P_{\eta} + \Delta P_{\tau} = \frac{12\times\eta\times Q\times L}{g^{3}\times w} + \frac{c\times\tau_{0}(H)\times L}{g} \tag{4.3}$$

Here, ΔP [Pa] is the pressure drop that is a sum of a viscous component, $\Delta P_{\eta}$ [Pa], and a field dependent induced yield stress component, $\Delta P_{\tau}$ [Pa]. Q [$m^3/s$] is the flowrate of MR fluid, whereas L [m], g [m] and w [m] represent respectively length, fluid gap and width of the flow orifice between the fixed magnetic poles. c is a dimensionless constant that varies between 2 and 3, depending on the ratio between the viscous component and the yield stress component. Equation (4.3) can be used for the design of MRF applications in valve mode, e.g. the minimum volume of active fluid can be established. $\tau_0(H)$ is the yield stress, defined in equation (4.2), and η is the dynamic viscosity (see equation (4.1)).

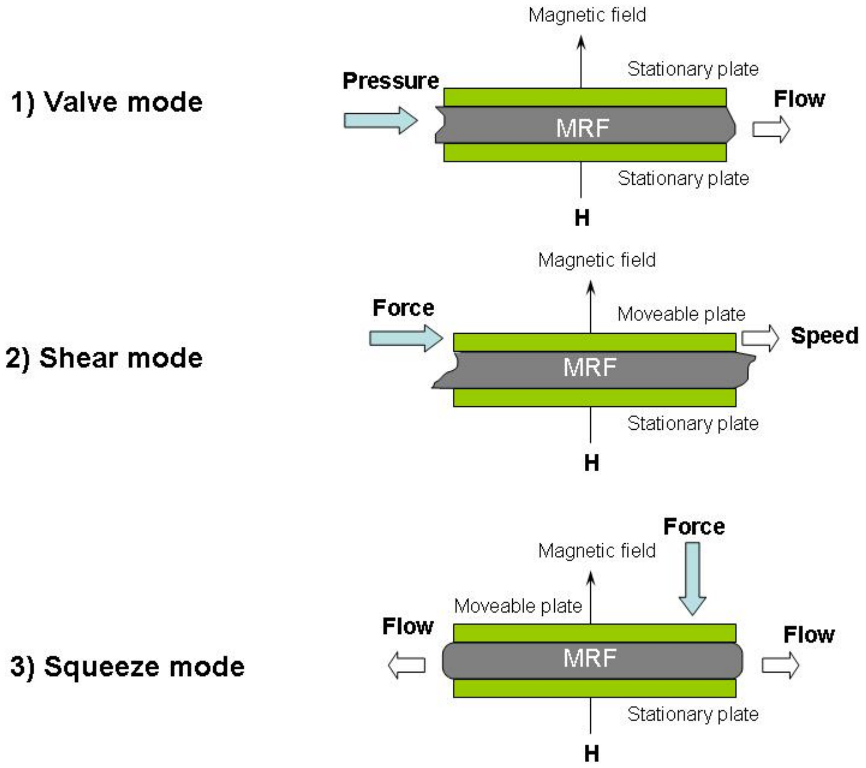

*Figure 4.7 – MR fluid operational modes*

Shear mode involves fluid between two plates that moves relative to one another, and is particular useful in clutches and brakes. Squeeze mode involves fluid between two plates moving in the direction perpendicular to their planes. This mode is not that well understood as the other modes, and few applications exist. One exception is use in some small-amplitude vibration dampers. In all the three cases mentioned above, the magnetic field is perpendicular to the planes of the plates in order to restrict the fluid in the direction parallel to the plates.

# 5 Applications of MR fluids in semi-active suspension systems

## 5.1 MR devices in automotive applications

Semi-active suspension elements containing MR fluid dampers have been used to some extent by the automotive industry. Since 2002, Cadillac has offered an MR semi-active suspension system in its premium vehicles (e.g. Seville STS, Escalade EXT). Other vehicles that incorporate such a system include e.g. Ferrari 599 GTB Fiorano and the new Audi TT. Secondary suspension systems for vehicles have also been using MR dampers. Rheonetic RD-1005-3 MR damper (manufactured by Lord Corporation) has been used successfully in semi-active seat suspension systems for large on and off-road vehicles.

## 5.2 MR dampers

As mentioned in section 5.1, MR dampers have been most widely used for commercial applications among MR devices. An MR damper is capable of responding quickly while providing large dynamic forces. An additional advantage is that, unlike hydraulic dampers, MR dampers do not require mechanical valves to restrict flow. Such a device has instead an electromagnetic coil incorporated into the piston while the reservoir is filled with an MR fluid. A magnetic field is developed in the angular orifice (see Figure 5.1) when a suitable current is applied. As a consequence, a yield stress is developed in the fluid as it passes through the flux path. This leads to an apparent increase in fluid viscosity.

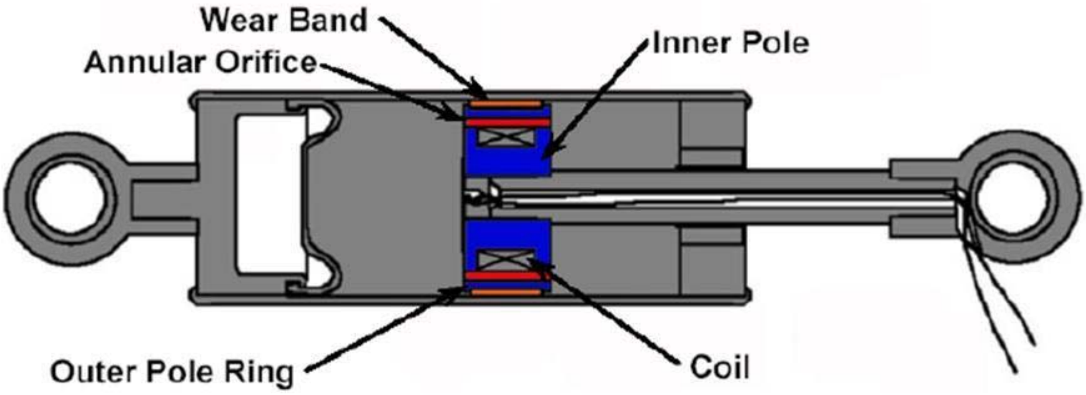

*Figure 5.1 – Schematic drawing of an MR fluid damper [6]*

MR fluid dampers are considered as semi-active damping elements due to their ability to offer controllable damping force, and with minimal power requirements. The benefit of using an MR fluid damper over a conventional passive damper is related to the force generated by the damper.

As seen in Figure 5.2, a linear viscous damper will generate a force proportional to the velocity. However, an MR damper is capable of generating a continuously variable force (within its range).

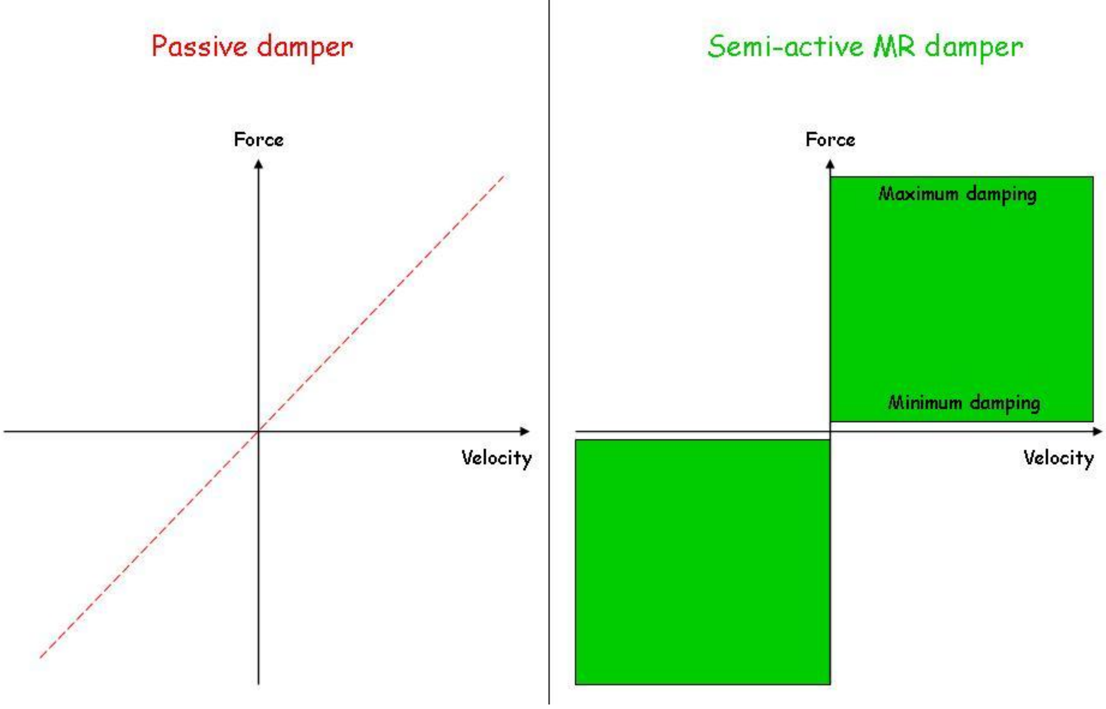

*Figure 5.2 – Passive damper characteristics vs. semi-active MR damper characteristics*

Currently, three main categories of MR dampers exist, including the mono tube (section view shown in Figure 5.3), the twin tube and the double-ended MR damper.

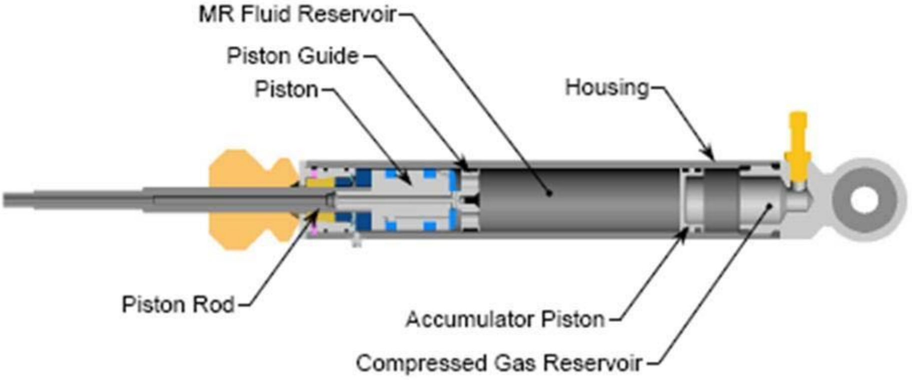

*Figure 5.3 – Mono tube MR damper [7]*

As seen in the figure above, a mono tube MR damper has only one reservoir for the MR fluid. An accumulator mechanism is used to accommodate the change in volume due to piston rod movement. The accumulator piston provides a barrier between the MR fluid and a compressed gas (normally nitrogen). The compressed gas is used in order to accommodate the volume changes that occur when the piston rod enters the housing.

The twin tube MR damper has two fluid reservoirs. As Figure 5.4 illustrates, one fluid reservoir is inside the other for such a damper. It has both an inner and outer housing, where the former guides the piston rod assembly in the same manner as in a mono tube damper. The inner reservoir is defined as the volume enclosed by the inner housing. The outer reservoir is defined as the volume between the inner housing and the outer housing. The inner reservoir is filled with an MR fluid. As a consequence, no air pockets exist in this area.

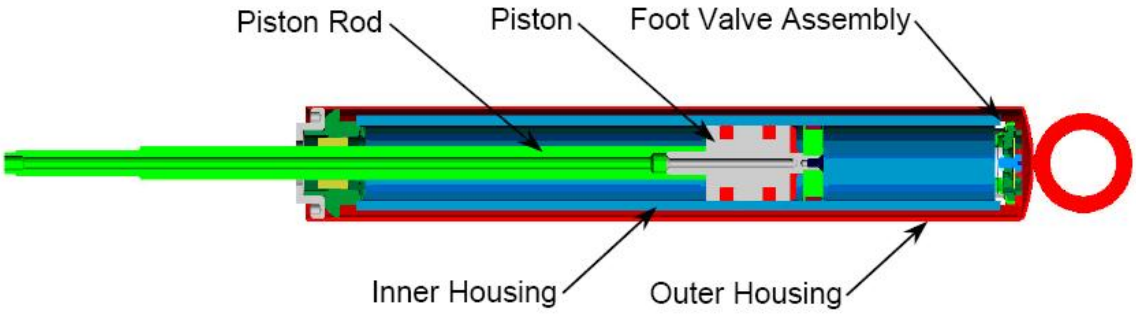

*Figure 5.4 – Twin tube MR damper [7]*

The outer reservoir, which is partially filled with MR fluid, is used to accommodate changes in volume due to piston rod movement. The outer tube therefore serves the same purpose as the pneumatic accumulator mechanism in mono tube dampers. A so-called foot valve is attached to the bottom of the inner housing, and is used to regulate the flow of fluid between the two reservoirs. When the piston rod enters the damper, MR fluid flows from the inner reservoir into the outer reservoir through a compression valve. The latter is a part of the foot valve assembly. When the piston rod is withdrawn from the damper, MR fluid flows in reverse direction (i.e. from the outer reservoir to the inner reservoir) through the return valve (also a part of the foot assembly).

The last type of MR damper is called a double-ended damper. This is due to a piston rod of equal diameter protruding from both ends of the damper housing. Double-ended MR dampers have been used for bicycle applications, gun recoil applications and for controlling building sway motion.

## 5.3 Mathematical model for an MRF damper

In order to study the performance of an MRF damper, a two DOF (degrees of freedom) quarter car model[4] is usually used (see e.g. [8]). The vehicle mass (including passengers) is represented by the sprung mass, illustrated by $m_2$ [kg] in Figure 5.5. The unsprung mass consists of the suspension components and the wheel (illustrated by $m_1$ [kg] in Figure 5.5). The first DOF is related to the independent motion of the sprung mass (often referred to as “body bounce”). The motion of the unsprung mass is the second DOF. The vertical displacement of the sprung mass is defined as $y_2$ [m], whereas the vertical displacement of the unsprung mass is defined as $y_1$. The input, due to the road profile, is defined as $y_0$ [m]. The suspension spring constant is $k_2$ [N/m], whereas the stiffness of the tire is defined as $k_1$ [N/m].

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[4] Analysing a system consisting of a quarter of the car

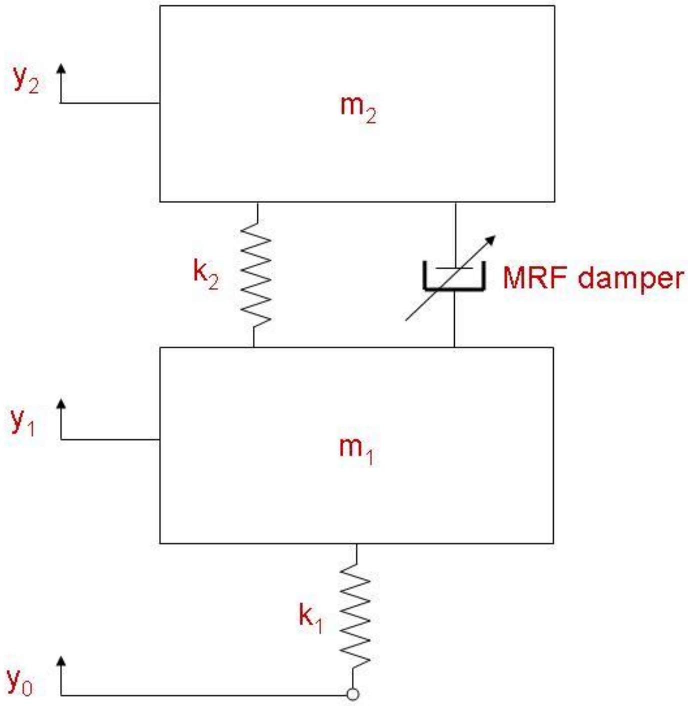

*Figure 5.5 – Quarter car model*

The following two equations can be derived for the system in Figure 5.5:

$$m_2 \ddot{y}_2 + k_2(y_2 - y_1) + F_d = 0 \tag{5.1}$$

$$m_1 \ddot{y}_1 - k_2(y_2 - y_1) + F - F_d = 0 \tag{5.2}$$

Here, $\ddot{y}_2$ is the acceleration [m/s$^2$] of the sprung mass (or the second derivative of the displacement of $y_2$), and $\ddot{y}_1$ is the acceleration [m/s$^2$] of the unsprung mass. $F_d$ [N] is the controllable MRF damper force, and F [N] is the change in the spring force from the static equilibrium condition. The controllable damper force consists of a viscous term, $F_v$ [N], and a term related to the magnetic behaviour of the MR fluid, $F_{MR}$ [N] (see equation (5.3)). The viscous force is also present even in the absence of the magnetic field. $F_{MR}$ is a controllable force component that can be varied by adjusting the applied current (see equation (5.4)).

$$F_d = F_v + F_{MR} \tag{5.3}$$

In addition, $F_{MR}$ can be expressed in the following way:

$$F_{MR} = \alpha i^{\beta} \tag{5.4}$$

Here, i [A] is the applied current, α [N/A] and β [1] are constants which are determined by the damper design and characteristics of the MR fluid. It is necessary to utilise a control algorithm in order to determine the appropriate magnetic field (i.e. current) required to generate the optimal MR force. Often, a continuous skyhook control algorithm is used in order to control the MRF damper (see e.g. [9]. This involves introducing, in the model, an additional shock absorber between the body and the inertia reference system.

## 5.4 Delphi MagneRide$^{TM}$

Delphi MagneRide$^{TM}$ is a real time semi-active suspension control system initially developed by Delphi Corporation in conjunction with Lord Corporation (see illustration in Figure 5.6). It is a continuously adaptive system with a closed feedback loop that can react to changes both in the road surface and the gear changes (front to back weight shift) within milliseconds.

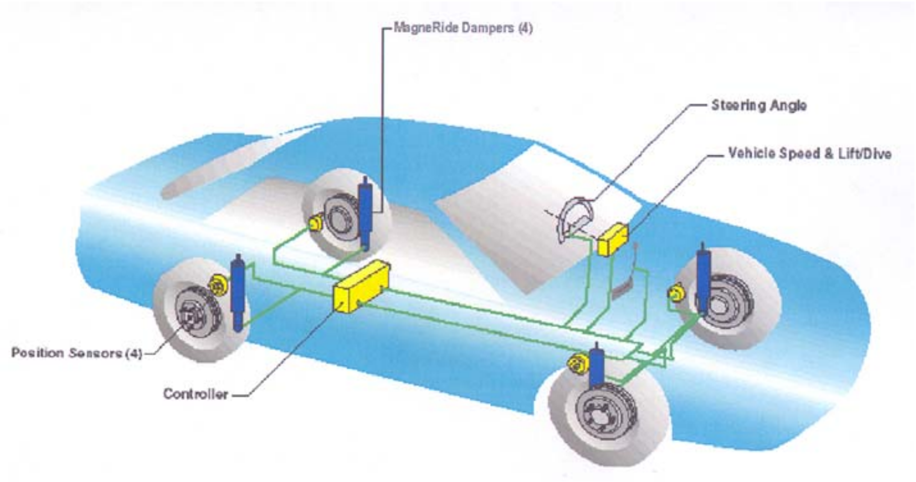

*Figure 5.6 – Illustration of the MagneRide system [10]*

The system consists of four MR fluid-based mono tube dampers (general description in Figure 5.3). In addition, the suspension system consists of a sensor set and an on-board electronic control unit. The central control unit sends signals to the coils on each damper. By varying the current through the coil in the damper piston, a variable resistance to fluid flow within the damper piston is obtained. Fine-tuning the current allows the generation of a wide range of damping forces. The central control unit is connected to complex force and acceleration sensing gauges. It is therefore constantly analysing what is happening with the car and thereby adjusts the damping settings accordingly. A continuously variable real-time damping system is obtained since changes in the damping force occur nearly instantaneously. Figure 5.7 shows a cutaway of a Delphi MagneRide$^{TM}$ shock absorber and a suspension strut.

*Figure 5.7 – Cutaway of rear shock absorber and suspension strut [11]*

Up to now, MagneRide$^{TM}$ has been installed in several passenger vehicles. This includes luxury automobiles, sports cars, light trucks and sport utility vehicles.

## 5.5 MR fluid technology in military vehicles

MillenWorks' active damper system (not a fully active suspension system) has, among others, been demonstrated with great success on the U.S. Army Stryker armoured combat vehicle (to the left in Figure 5.8). Around 2005, MillenWorks' magneto-rheological optimised active damper suspension (MROADS) system was tested head-to-head against a stock suspension system for the Stryker at the Yuma proving ground in Arizona. A huge increase in off-road mobility and on-road handling was experienced with the MROADS Stryker.

The core of the MROADS system tested on the Stryker included 8 dampers and controllers. Proprietary algorithms were used in order to modulate individual wheel forces within 4 ms in response to terrain inputs and body motion. Full functionality of the stock Stryker vehicle's pressurised gas spring ride height management system was maintained while integrating the MR technology into the physical envelope of the original damper.

Comparison measurements regarding mobility showed great results for the retrofitted Stryker vehicle, meaning that Stryker vehicles could be retrofitted with MR systems in the future. Results showed that on different off-road bump courses, the MROADS Styker proved to be 40 – 60 % faster than the original stock vehicle while maintaining the same level of absorbed power (which is a measure of transmitted vibration). The retrofitted vehicle also showed an increase in the vehicle's 6-watt absorbed power speed from 36 (stock vehicle) to 61 km/h. In addition, improved vehicle platform stability was observed by drivers and bystanders. Marked improvements during aggressive on-road manoeuvres (like lane changes) were also achieved.

The MROADS system has also been tested in the HMMWV Hummer (to the right in Figure 5.8). The system was designed to facilitate bolt-on retrofitting. Only minor modifications were made to the HMMWV in order to mount sensing and control hardware. The original chassis and lower A-arm suspension mounting holes were used to accommodate the MR damper and spring assembly.

*Figure 5.8 – Vehicles fitted with the MROADS system (Stryker and HMMWV) [12]*

The MROADS system integrated on the HMMWV was tested in the California dessert. Again, tests showed significant reduction in absorbed power. Additional advantages observed or measured include:

- ✓ Higher speeds over a given terrain
- ✓ Improved tire traction
- ✓ Improved tire life
- ✓ Reduced fatigue loading of vehicle structure and payload
- ✓ Reduced driver, vehicle and payload damage from terrain impacts when moving
- ✓ Improved vehicle stability and handling
- ✓ Improved accuracy during surveillance, targeting or weapons firing

According to MillenWorks, it is possible to scale the MROADS system to suit different applications (i.e. vehicles). So far, integration of the system has been successfully demonstrated on two different classes of military vehicles. In addition, MillenWorks has developed a light utility vehicle (see Figure 5.9) for demonstrating controllable vehicle technologies, including among others all wheel parallel hybrid powertrain and semi-active suspension using magneto-rheological struts.

*Figure 5.9 – Light utility vehicle with semi-active suspension [13]*

# 6 Concluding remarks

A controllable suspension system (semi-active or active) is capable of improving both ride and handling characteristics for a military vehicle. A semi-active suspension system is a good compromise between a passive and an active suspension system, where the latter is capable of providing both excellent ride and excellent handling. While an active system requires additional energy in order to operate, a semi-active suspension system has in principle no external energy requirement (a small amount is though necessary for control purposes). Another advantage with the latter system is less complexity compared to an active system, something that is very useful regarding maintenance work during military operations. In addition, semi-active suspension systems have much better performance characteristics than passive systems.

Semi-active suspension systems using MR fluids have been used to some extent by the automotive industry. In addition, some research projects exist where such systems have been integrated into military vehicles (e.g. Stryker and HMMWV). MR fluids are characterised as controllable fluids that are manufactured by suspending ferromagnetic particles in a carrier fluid. When being exposed to a magnetic field, MR fluids have the ability to reversibly change from viscous liquids to semi-solids within milliseconds. This feature makes it possible to control the fluid's rheological properties, including the viscosity. An MR damper is capable of responding quickly (within milliseconds) while providing large dynamic forces. An additional advantage is that, unlike hydraulic dampers, MR dampers do not require mechanical valves to restrict flow. Compared to electro-rheological (ER) fluids (another class of controllable fluids), MR fluids have some additional advantages. This includes higher control effect than the equivalent ER fluid products. In addition, there is a better stability regarding contaminants for MR fluids. Initially, MR fluid technology had some challenges regarding non-predictable fluid behaviour. This was related to in-use thickening, sedimentation and abrasion. Extensive studies related to these issues have been completed during the last few years, and some of these challenges are now solved.

Another drawback with semi-active suspension systems using MR fluids is that MR fluids are rather expensive to purchase.
As pointed out in chapter 3, controllable suspension systems, including semi-active systems, offer a lot of opportunities that can improve the performance of a military vehicle. Such systems can clearly have a positive impact on health and comfort factors for occupants in a military vehicle. This is due to reduced vibrations in critical frequency ranges. A controllable suspension system can also improve the tactical mobility of vehicle, since a reduction in absorbed power is experienced for a given velocity. This means that it is possible to have a higher velocity over a given terrain. An increased mobility will also make it easier for the vehicle to avoid encounter (i.e. manoeuvre out-of-contact). In addition, the ability to move faster over a rough terrain can also contribute to avoiding being hit. The probability of hit feature (i.e. the enemy) will most likely also increase with such a system integrated in the vehicle, since a reduction in the movement of the weapon system can be accomplished. Controllable suspension systems can also give addition benefits, e.g. increased payload, increased durability of the vehicle, increased operational range and more consistent driving characteristics.

A semi-active suspension system (using MR fluids) integrated in a military vehicle will add complexity to the vehicle, that is, compared to a conventional (passive) suspension system. This could have a significant impact on maintenance needs. If electronic components and software systems are introduced as a part of the suspension system, significantly higher educated maintenance crews will be necessary to keep the system running. Electronic components and software systems also need to be taken into account regarding reliability, reparability and obsolescence issues. Another current disadvantage with controllable suspension systems is that, up to now, only research projects exist, leading to a lack of field experience.

Regarding military vehicles, semi-active suspension systems can probably be considered as the optimal solution, and not as a compromise. Such a system has many of the advantages that an active suspension system has regarding performance. If one compares the performance of a semi-active and an active suspension system with a passive one, most of the improvements regarding comfort and safety are also achieved by a semi-active system. It is though obvious that a fully active system will perform better in nearly all circumstances, but the additional cost and complexity of such a system are perhaps not worthwhile. As discussed in this report, semi-active suspension systems using MR fluids have been integrated in a few military vehicles with great success. In addition, semi-active systems based on other principles have been demonstrated in other types of military vehicles. In Germany, an ER system has been demonstrated in both a Dingo 2 and a 5 ton lorry. This work was performed in collaboration between Fluidicon and WTD 41. Another system, based on hydraulics, has been integrated in a tracked vehicle (Wiesel). This is another German collaboration between among others WTD 41 and the University of Paderborn.

According to the results from both U.S. (Stryker and HMMVW) and Germany, semi-active suspension systems seem to be cost effective regarding series production for use in military vehicles. In addition, such systems can be retrofitted into existing vehicles (as examples already have shown). As discussed above, the drawbacks with semi-active suspension systems are related to cost and complexity. These factors must clearly be set up against the increased vehicle performance when deciding to install such a system. However, as semi-active suspension systems become more and more common in regular automobile applications, and thereby more mature and cheaper, it is likely that at least new military vehicles will be equipped with such systems in the future.

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[13] "MillenWorks," 2007.

# Appendix A Abbreviations

| | |
|---|---|
| $C^2IS$ | Command, Control & Information System |
| DOF | Degrees of Freedom |
| ER | Electro-Rheological |
| HMMWV | High Mobility Multipurpose Wheeled Vehicle |
| MR | Magneto-Rheological |
| MRF | Magneto-Rheological Fluid |
| MROADS | Magneto-Rheological Optimised Active Damper Suspension |
| NIAG | NATO Industry Advisory Group |
| rms | Root Mean Squared |
| TEKNISK | Teknologier for nettverksintegrert stridskjøretøy |
| WBV | Whole-Body-Vibration |
| WTD | Wehrtechnische Dienststelle |