PERFORMANCE ANALYSIS OF A NEW COMPACT MAGNETO-RHEOLOGICAL PROPORTIONAL CONTROL VALVE FOR HYDRAULIC ACTUATION USING FEM AND EXPERIMENTAL APPROACH

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Performance analysis of a new compact magneto-rheological proportional control valve for hydraulic actuation using FEM and experimental approach

by

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Maher Yahya Salloom

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List of Abbreviations

FEMM	Finite Elements Method Magnetics
MR	Magneto-Rheological

List of Symbols

A	Piston area (cm^2)
B	Magnetic flux density (Tesla)
c	Constant
d	Gap thickness (m)
g	Gap thickness (m)
g	Gravity acceleration (m/s^2)
g_x	Gap thickness along X axis (m)
h	Gap thickness (m)
h_a	Lower limit of MR fluid velocity profile (m)
h_b	Upper limit of MR fluid velocity profile (m)
H	Magnetic field strength (A/m)
h_a	Lower limit of gap (m)
h_b	Upper limit of gap (m)
I	Current (A)
L	length of flow channel (m)
L_{active}	Active core length (m)
L_{g1}	Gap length in the side of MR valve (m)
L_{g2}	Gap length in the middle of MR valve (m)
L_{mr}	Gap length (m)
L_{steel}	Total length of magnetic flux path (m)
L_t	Total gap length of MR valve (m)
L_1	Gap length in the middle of MR valve (m)
N	Number of turn of coil (turn)
P	Fluid pressure (Pa)
P_{η}	Pressure viscosity component(Pa)
P_{τ}	Pressure yield stress component (Pa)
Q	Flow rate (cm^3/sec)
R	Mean radius (m)
R_g	Outer radius of annular channel (m)
R_1	Resistors (Ω)

r_o	Inner radius of disk (m)
R_o	Outer radius of disk (inner radius of annular channel) (m)
s	Stroke (cm)
T	Temperature (Kelvin)
t	Time (sec)
u	velocity of MR fluid (cm/sec)
u_m	Mean velocity of MR fluid (cm/sec)
u_p	MR fluid velocity profile (cm/sec)
V	Oil volume (m^3)
v	Velocity (cm/sec)
W	Width of flow channel (m)
γ^o	Shear rate
δ	MR fluid plug thickness (m)
ΔP	Pressure drops (Pa)
ΔP_a	Pressure drops of disk type of MR valve(Pa)
ΔP_c	Pressure drops of annual type of MR valve (Pa)
ΔP_{η}	Pressure drops viscosity component(Pa)
ΔP_{τ}	Pressure drops yield stress component (Pa)
η	Viscosity (Pa.s)
μ_o	Relative permeability of air
μ_r	Relative material permeability
ρ	Density (kg/m^3)
τ	Shear stress (Pa)
τ_y	Dynamic yield shear stress (Pa)
τ_o	Yield shear stress (Pa)
Φ	Iron particles loading
θ	Angle between two pair of iron particles

List of Publications

1- Salloom, M. Y. and Samad, Z., (2011) "Finite element modeling and simulation of proposed design magneto-rheological valve", *The International Journal of Advanced Manufacturing Technology*, Vol. 54 pp 421–429

2- Salloom, M. Y. and Samad, Z., (2011) "Magneto-rheological directional control valve", *The International Journal of Advanced Manufacturing Technology*, Online 2 June (DOI) 10.1007/s00170-011-3377

3- Samad, Z. and. Salloom, M. Y. and Hawary, A. F., (2011) "Simulation and Design Optimization of Magneto-Rheological Control Valve ", *International Journal of Mechanical and Materials Engineering,* (Accepted 10 June) No. 10046

4- Salloom, M. Y. and Samad, Z., (2011) " Experimental test of Magneto-Rheological Directional Control Valve ", *Advanced Materials Research* Vols. 383-390 (2012) pp 5409-5413

5- Salloom, M. Y. and Samad, Z., (2010) " Design and Modelling Magneto-Rheological directional control valve ", *Journal of Intelligent Material Systems and Structures,* submitted on 19/8/2010 (under review ID JIM-10-132.R1)

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8- Samad, Z. and Salloom, M. Y. , (2011) " Design and Manufacture of Magneto-Rheological Directional Control Valve", The 4th Regional Conference on Manufacturing Yogyakarta, 9-10 November 2011, accepted on 10/2011.

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Analisis prestasi injap kawalan berkadaran magneto-reologi padat baru untuk penggerakan hidraulik menggunakan FEM dan pendekatan eksperimen

Abstrak

Salah satu bahagian utama dalam sistem hidraulik ialah injap kawalan arah, yang diperlukan bagi mengawal pengerak hidraulik. Injap magneto-reologi (MR) telah terbukti boleh menggantikan injap kawalan arah hidraulik bagi mengawal penggerak hidraulik oleh beberapa penyelidik dalam bentuk susunan titi Wheatstone empat set injap MR dengan bahagian tidak bergerak. Walau bagaimanapun, perkiraan itu tidak padat dalam satu unit. Secara umumnya, unit padat adalah lebih praktikal untuk digunakan dalam sistem hidraulik.Oleh itu, satu reka bentuk baru perlu dipertimbangkan untuk menghasilkan unit padat. Objektif-objektif utama penyelidikan ini adalah untuk mereka bentuk injap kawalan arah berkadaran MR dengan menggunakan bendalir MR, untuk menganalisis rangkaian magnet dengan menggunakan perisian FEMM, dan mengkaji dan mensimulasikan prestasi injap ini. Dalam penyelidikan ini, satu kajian ilmiah yang komprehensif tentang kemajuan teknologi ini memberikan pemahaman yang berharga berkaitan reka bentuk injap MR daripada para penyelidik sebelum ini. Reka bentuk bagi injap kawalan arah MR, binaan dan prinsip operasi dibentangkan. Reka bentuk injap tunggal MR yang dicadangkan telah membolehkan pembangunan injap kawalan arah MR. Reka bentuk dan analisis unsur terhingga menggunakan perisian FEMM bagi injap tunggal MR dan injap kawalan arah MR telah dilakukan untuk mendapatkan reka bentuk yang optimum. Injap tersebuat telah difabrikasi dan rig eksperimen untuk menguji injap telah dibangunkan. Persembahan ujikaji untuk prinsip kerja fungsi injap dan prestasi injap ditunjukkan. Keputusan simulasi menunjukkan bahawa injap bekerja dalam mengawal arah dan kelajuan penggerak hidraulik. Injap boleh dikendalikan dengan kadar aliran bolehubah dengan mengubah arus elektrik.

Didapati bahawa arus elektrik berkadaran songsang dangan kadar aliran. Arus tinggi menghasilkan kadar aliran rendah dan sebaliknya. Ia melaksanakan kerja injap bagi mengawal penggerak hidraulik secara berkadaran. Injap boleh dikendalikan sebagai injap kawalan arah ON-OFF serta injap kawalan arah berkadaran dengan '*meter-in*' atau '*meter-out*' dengan menukar sambungan elektrik.

Performance analysis of a new compact magneto-rheological proportional control valve for hydraulic actuation using FEM and experimental approach

Abstract

One of the main parts in a hydraulic system is the directional control valve, which is needed in order to operate an hydraulic actuator. The magneto-rheological (MR) valve has been proven can replace hydraulic directional control valve for controlling hydraulic actuator by few researcher in the form of Wheatstone bridge arrangement of four set of MR valve with no moving part. However, the arrangement is not compact in one unit. Generally, compact unit is more practical to be used in hydraulic system. Thus, a new design needs to be considered to produce compact unit. The main objectives of this present research are to design a MR directional control valve using MR fluid, to analyse its magnetic circuit using FEMM software, and to study and simulate the performance of this valve. In this research, a comprehensive literature review on the advancement of this technology provides valuable insight on MR valve design by previous researchers. The design of MR directional control valve, the construction of the valve and the principle of work are presented. The design of proposed MR single valve has enabled the development of the MR directional control valve. Design and finite element analysis using FEMM software of the MR single valve and MR directional control valve were done to obtain the optimal design. The valve was fabricated and the experimental rig for valve test was developed. The experiment presentations for functional working principle of the valve and valve performance were shown. The results of the simulation show that the valve works in controlling the direction and the speed of hydraulic actuators. The valve can be operated with variable flow rate by varying the electric current. It is found that the electric current is inversely proportional to the flow rate. High current produces low flow rate and vice versa. It does the work of the

valves to proportionally control the hydraulic actuators. The valve can be operated as ON-OFF directional control valve as well as proportional directional control valve with meter-in or meter-out by changing electric connection.

Chapter 1 – Introduction

This chapter describes the background of the research including the magneto-rheological (MR) fluid definition and the motivation for this work. The problem statements, the objectives and the scope of work are also presented. With objectives identified, the means by which the objective will be met are discussed. Finally, the outlines of this document conclude the chapter.

1.1 Background

Magneto-rheological (MR) fluid is a fascinating material, composed of micro-sized magnetic particles suspended in liquid such as hydrocarbon oil and silicon oil. The rheological properties of MR fluid can be rapidly and reversibly altered when an external magnetic field is applied. The suspended particles in the MR fluid become magnetized and align themselves like chains with the direction of the magnetic field. The formulation of these particle chains restricts the movement of the MR fluid, thereby increasing the yield stress of the fluids. The critical rheological characteristics of an MR fluid are its yield strength, viscosity and settling rate (Turczyn and Kciuk, 2008). The yield strength and viscosity of an MR fluid can be continuously varied using appropriate magnetic fields. Due to these unique properties of MR fluid, it has been used in various commercial applications.

MR fluids have found use in optical polishing, MR fluid clutches, vibration isolation systems and a variety of aerospace applications, civil engineering applications and automotive damping applications. In addition, the MR fluid is one of the most efficient means to interface mechanical components with electronic controls, offering fast speed of switching and continuously variable control. Designs that take advantage of MR fluids are potentially simpler and more reliable than conventional electromechanical devices (Jolly, et al., 2000).

One of the main parts in hydraulic system is directional control valve. Four ways three positions (4/3) directional control valve controls flow direction of hydraulic oil that is needed in order to operate hydraulic actuators. Spool type is one of these types in which is the spool slide inside it to change the direction of fluid flow. Directional control valve spool type requires good maintenance (Doddannaver and Barnard, 2005). The mating surfaces of the valves may damage (Pinches, 1989), if the hydraulic oil is dirty, causing them to lose their accuracy. Dirt will cause these valves to stick or work erratically (Pinches, 1989). In addition, spool valves must be accurately machined and fitted to their bores. Using MR fluid technology, (4/3) directional control valve can be designed without the spool to eliminate the above mentioned problems.

MR fluid is controllable fluid which was discovered by Rabinow and Winslow's in 1940's. MR fluid has received a great deal of attention over the past ten years (Jolly, et al., 2000), because it offers the promise of valve with no moving parts, low-cost control, and miniaturization. MR fluid can be interfaced between magnetic field and fluid power without the need for mechanical moving parts like spool in directional control valves.

There have been many researches done on MR valves. Yoo and Wereley (2002) have designed the miniature MR valve with the maximum performance of MR effect in fluid mechanics. Ai et al. (2006) have designed a MR valve possessing simultaneously annular fluid resistance channels and radial flow resistance channels. Yokota et al. (1999) have proposed and fabricated a pressure control valve using MR fluid. Songjing et al., (2002) have developed a new type MR fluid relief valve.

There are only three researches (Yoo and Wereley, 2004; Yoo et al., 2005; John et al., 2008) found attempting to control the direction of hydraulic cylinder. They have successfully proven that MR fluid can be utilized to control the direction of hydraulic cylinder without spool, by connecting a set of single MR valves. They have arranged a set of four MR valves as Wheatstone bridge, implemented on hydraulic control circuits to operate a hydraulic actuator, but not as a compact unit like hydraulic directional control valve. Yoo and Wereley (2004) have employed this configuration combined with a gear pump as hydraulic power source. Yoo et al. (2005) have described the concepts of combination between a piezo-pump and a MR valve. John et al. (2008) have developed the hydraulic actuator system consisting of MR valves with a terfenol-D actuated pump as the pressure source. In fact, they have not mentioned any suggestion related to make compact MR directional valve.

1.2 Problem statements

Till now, most of the research efforts are concentrated on the development of a single MR valve. As mentioned above, only Yoo and Wereley (2004), Yoo et al. (2005) and John et al. (2008) have used an arrangement of a set of four MR valves as a Wheatstone bridge utilized as a hydraulic control circuit to operate a hydraulic actuator. These arrangements have achieved the control of the actuator direction, but it was not compacted in one unit. There after no other related activity has been published in literature on compact MR directional valve. Generally, compact units are more practical to the use in hydraulic systems. The significance of this work is that design a new type of directional control valve utilizing MR fluid technology. A further development in the design of MR directional valve for hydraulic system has been studied, in order to improve it and make it to be more suitable with hydraulic systems. This has been visualized by using a combined set of single MR valves to act as a compact unit which is easy to install among hydraulic components. Moreover, simplicity in manufacturing was kept as a priority.

The design concept of compact MR directional valve is to use four single MR valves arranged in a Wheatstone bridge circuit concept. An appropriate single MR valve should be suitable for the use in a compact MR directional valve, as well as, it should achieve a good performance. There is no suitable design readily found in pervious literature, also no previous investigation of the configurations in operation and how to operate these configurations were found. Those configurations give more flexibility of hydraulic circuits design depending on the type of applications.

The problem to be tackled in this work is about, how to develop and prove of concept of MR directional valve appropriate to be used in hydraulic control system utilizing MR fluid. To add more to the efforts made by previous works in the MR fluid technique, an investigation is required in the field of MR directional valve system answering the following research questions:-

1- How to design a single MR valve which is suitable for development of MR directional valve?
2- How to design a MR directional valve which is compact, in order to control the flow of MR fluid, without the need of moving parts inside the valve such as in the case of conventional and proportional valve of hydraulic system?
3- How to design an electrical circuit that has to control the current of the coil which may change the configuration of operations?

MR fluid is a class of smart material whose rheological properties may rapidly be varied by the application of a magnetic field. This would allow the development of directional control valves having no moving parts. The performance of this valve will be computationally simulated and experimentally tested as a system of MR directional control valve in the presence of a hydraulic actuator. The MR directional valve can be used to replace a four ways three position (4/3) directional control valve with different centre positions. The flow of MR fluid to a hydraulic actuator that is controlled by using the proposed MR directional valve system will be studied.

1.3 Objectives

The main objective of this present research is to study the performance of new compact proportional control MR valve using FEM. This will lead to several objectives :-

1- To propose and optimize a radial and annular design of single MR valve using MR fluid and evaluate the performance using FEMM software and mathematical model.

2- To design a compact MR directional valve system utilizing a new single MR valve as an element.

3- To prove the operational functionality of MR directional valve using proposed electrical circuit and to study the configuration of operation.

4- To investigate the performance characteristics of MR directional valve operations experimentally when it is connected to a hydraulic actuator.

1.4 Scope of work

The scope of the present work is to design a new hydraulic directional control valve that operates without the need of moving part, which exists in traditional model of hydraulic valves, by mainly relying on the use of MR fluid technology.

The scope also covers preliminarily and detailed design of single MR valve, which enable the design of MR directional control valve. Moreover, it includes the use of FEM technique to analyse magnetic circuits to help in assessing the performance of such systems. In addition to what has been mentioned above, the scope also include building up of such system and testing its performance experimentally.

1.5 Research Approach

Owing to the complexity of the project, it was decided to tackle the problem in a step wise manner. The first stage includes the development of single MR valve which fulfils the requirements set by previous research works. It is found that this valve should meet the specification of MR fluid technology. Moreover, it should be appropriate for the use in the present desired process. The magnetic circuit analysis of the valve enables the simulation of the valve performance computationally.

In the second stage of this work, a system of multi single MR valve will be designed in detail to perform as an MR directional valve. Similarly, a magnetic circuit analysis of this arrangement will be done computationally. In the third stage, the MR directional valve system will be fabricated and its performance will be experimentally tested. In the final stage, the MR directional valve system will be connected to hydraulic cylinder to be operated as an integrated system and its performance as one unit will be examined in the presence of an actuator.

1.6 Organization of thesis

The thesis is organized into five chapters. Chapter One gives the background of the research including the magneto-rheological (MR) fluid definition and the motivation for this work. The problem statements, the objectives, the scope of work and research approach are also presented. With objectives identified, the means by which the objective will be met are discussed.

Chapter Two reviews literature on MR fluid, properties of MR fluid, MR fluid application, MR fluid modes and MR fluid models. Previous works have been reviewed to investigate the past researches in relation to this work. The area of MR fluid, MR damper, MR valve design and magneto-rheological systems are of primary interest.

Chapter Three describes the research methodology for achieving the objectives. The methodology flow chart is presented. The review of MR valve designs from past works, the proposal of a new MR valve design, the selection of a single MR valve design for use in MR directional valve, and the theoretical modelling of MR valves are carried out. The FEM analysis of magnetic model for MR valve using FEMM software, the performance simulation of MR valve using magnetic field obtained from FEMM software data, and the MR valve design optimization are also carried out. The mechanical design of MR directional control valve, the MR directional valve components fabrication and assembly, the integration of electrical components for the system, instruments and hydraulic system, and the electrical circuit and instruments equipped with the new proposed MR directional valve are described in details. Finally, the experimental works, including adjusting the instruments, acquiring materials for preparing MR fluid, mixing MR fluid, collecting result and analysing data, are presented.

Chapter Four presents the results of each steps of research methodology in details separately. Results of MR valve design, optimization, comparison between MR valves, finite element analysis, MR directional valve operation, determining operating range and experiment are presented. It is followed by the discussion on the outcomes of the results.

Chapter Five summarizes the results from the research conducted. It is followed by the research conclusions. Next, the contributions of this research are highlighted. Finally, few suggestions are recommended for future work.

Chapter 2 – Literature Survey

A literature survey has been done to investigate the past researches in relation to this work. The area of MR fluid, MR damper, MR valve design and magneto-rheological systems are of primary interest.

2.1 Magneto-rheological (MR) fluid

MR fluid is a non-colloidal fluid. MR fluid consists of soft micron sized magnetic particles (typically, 3–10 μm carbonyl iron) suspended in hydrocarbon oil or silicone oil. MR fluid is different from colloidal ferro-fluid, in which the particles are 1000 times smaller (Olabi and Grunwald, 2007). In MR fluid, each particle of iron has a natural magnetic dipole. The magneto-rheological response of MR fluid results from the polarization induced in suspended particles by application of an external field, which results in magneto-rheological effect of the MR fluid, with a change in rheological behaviour. Typically, this change appears due to the development of a yield shear stress that proportionally increases with the applied magnetic field. The magneto-rheological effect directly influences the mechanical properties of the MR fluid. The suspended particles in the MR fluid become magnetized and align themselves, like chains, with the direction of the magnetic field (Jolly et al., 2000). The formulation of these particle chains restricts the movement of the MR fluid, thereby increasing the yield stress of the fluids. The force of attraction between the particles in the chains appears as a resistance to shear deformation and restricts fluid flow.

In an idealized MR fluid, the fluid does not start flowing till a particular value of shear stress, called the yield shear stress, has been reached. Thus, the viscosity of these fluids can be changed using an external magnetic field. (see Figure 2-1).

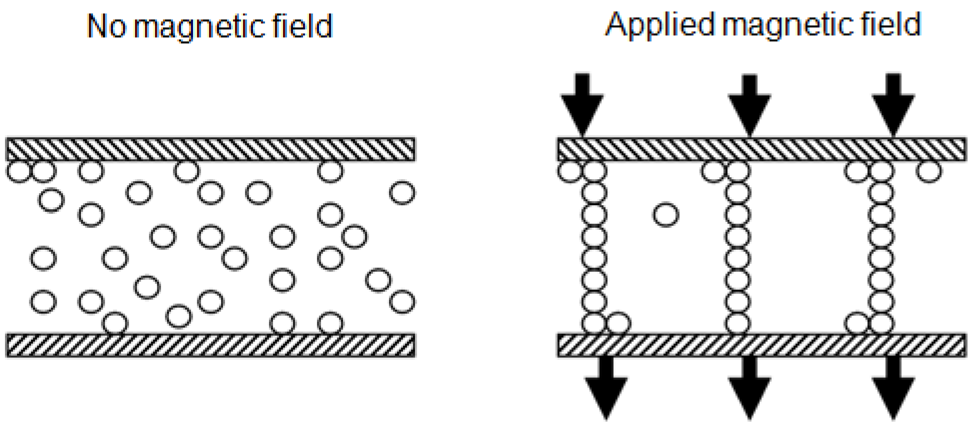

Figure 2-1 The formation of MR fluid under the applied magnetic field (Kciuk and Turczyn, 2006)

The rheological behaviour of MR fluid flow through their gap between two plates under magnetic field was studied by Bossis et al. (2002). They described the model of structure for MR fluid based on a cubic network of infinite chains of particles aligned along with the direction of the magnetic field, *H*.

These chains are of deforming relevance when the material is strained (see Figure 2-2). Any pair of neighbours in the chains has the same distance between them. The angle, θ, increases at the same rate with that of the strain of the fluid. The interactions between the magnetic forces of the particles are responsible for making the suspension becomes like a gel. Hydrodynamic forces will break this gel and allow the suspension to flow. The relationship between the shear stress and the shear rate and their relationship between the viscosity and the shear rate depend on the fluid type. Referring to Figure 2-3, the fluid can be recognized as a Newtonian fluid (King, 2002).

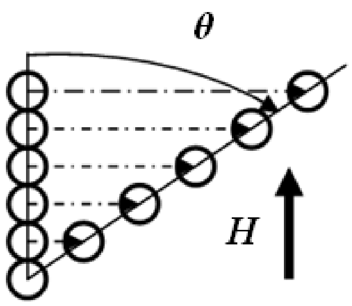

Figure 2-2 Deformation of strained particles (Bossis et al., 2002)

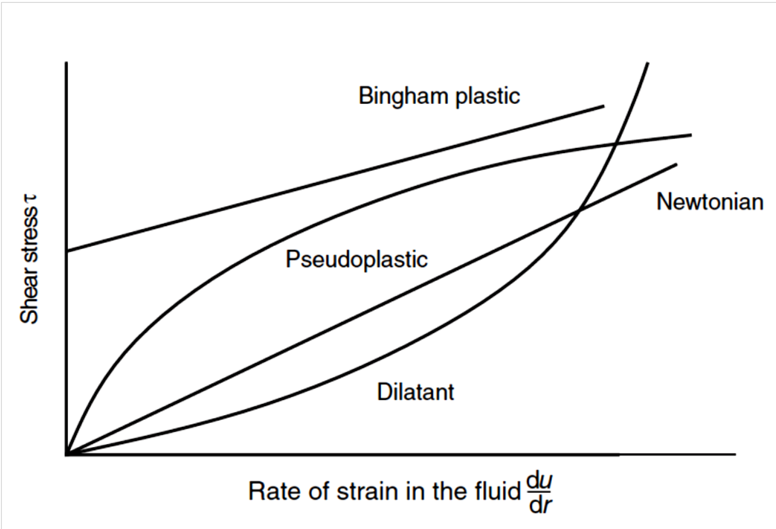

Figure 2-3 Shear stress and shear rate relationship and viscosity and shear rate relationship of MR fluid (King, 2002)

The viscosity does not change with different shear rate values, and the shear stress has a linear relationship with the shear rate. The shear stress has a reducing (Pseudoplastic Curve) or increasing (Dilatant Curve) dependency with shear rate.

There is an analogous relationship between viscosity and shear rate, which corresponds to each of these fluid behaviours. These behaviours are similar to those observed in ketchup, tooth pastes, etc (Olabi and Grunwald, 2007). The Bingham plastic curves describe behaviour of MR fluid. MR fluid without magnetic field behaves like an ordinary Newtonian fluid. It is very similar to carrier fluids, except that the metal powder content of MR fluid makes the liquid slightly thicker.

2.1.1 Properties of MR fluid

The mechanical energy required to yield the formation of MR fluid increases with the increase in magnetic field resulting in the yield shear stress to increase as well. Typical values of the maximum achievable yield strength are given in Table 2-1. It is observed that MR fluid behaves like Newtonian fluids when there is no magnetic field applied. MR fluids performances are limited by the magnetic saturation of the particles. Iron particles have the highest magnetic saturation.

Table 2-1 MR fluid properties (Kciuk and Turczyn, 2006)

Property	MR fluid
Yield Stress τ	50 - 100 k Pa
Maximum magnetic field	150 -250 kA/m
Viscosity η (at 25^o C under no magnetic field)	0.2 - 0.3 Pa.s
Density	3 - 4 g/cm^3

2.1.2 MR fluid application

The important rheological characteristics of an MR fluid are its yield force and viscosity. The yield force and viscosity of an MR fluid can be continuously varied using appropriate magnetic fields. Using this property, control schemes can be implemented in devices using MR fluids.

Designs that take advantage of controllable fluids are more reliable than conventional electro mechanical devices and potentially simpler (Jolly et al., 2000). In addition, the MR fluid is one of the most efficient means to interface, mechanical components with electronic controls (Mechatronics), offering fast switching speed, miniaturization, and continuously variable control (Ai et al., 2006). Although research is still ongoing, there are many commercial applications which have begun to spread, as well as devices that use MR fluid. More common applications are devices used in vehicles. These devices include dampers which are used in the suspension systems of the vehicles (see Figure 2-4). This is sought out by many researchers in the development such as Letelier et al.(2009); Anderson et al.(2008); Choi and Soung (2008); Chooi and Oyadiji (2008); Ayder et al.(2007); Lam and Liao (2003). They also include brake systems which researchers sought to develop (Sukhwani and Hirani, 2008; Kerem et al., 2008; Park et al., 2006; 2008) as well as for clutch in automotive discipline case (Smith et al., 2007; Kavlicoglu et al., 2006; Yalcintas, 1999). These dampers are not only for automotive applications, but also for motorcycle and bicycle applications (Battrebee and Sims, 2009; Ahmadian and Gravatt, 2004; Ericksen and Gordaninejad, 2003). They have also been used for vibration isolation in the helicopter applications (Hu and Wereley, 2008; Choi and Wereley, 2005; Kamath et al., 1998), for aircraft landing gears (Battrebee et al., 2007a and 2007b), for train suspension (Lau and Liao, 2005) and for washing machine (Spelta et al., 2009). Dampers are also used in civil engineering applications such as for isolating buildings and bridges from earthquake (Fan et al., 2009; Guo et al., 2009; Qu and Tu 2009; Fujitani et al., 2003).

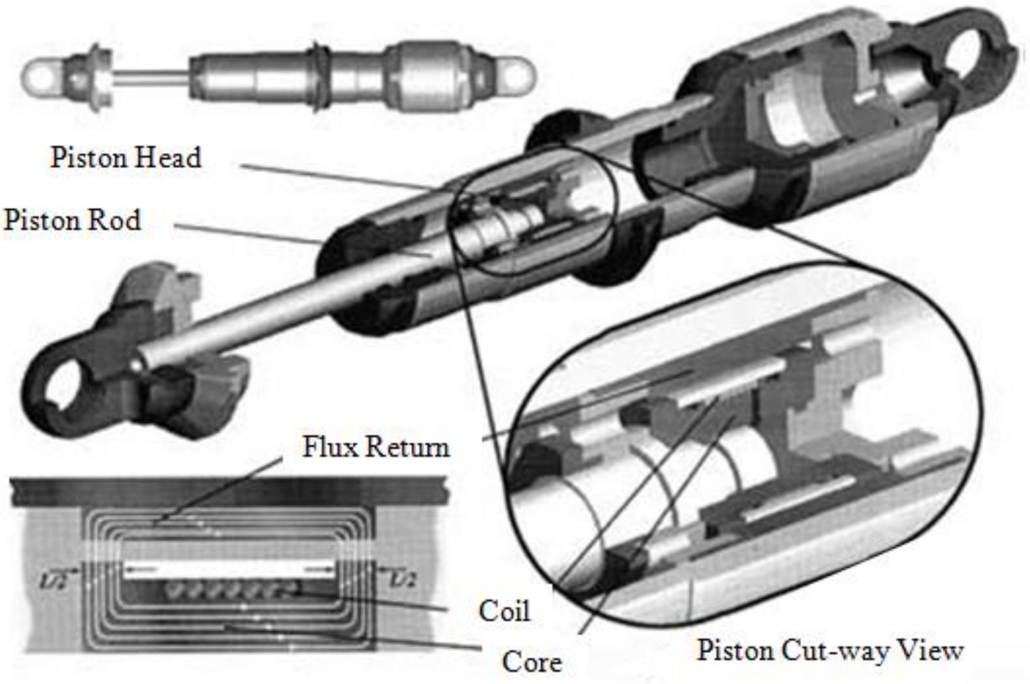

Figure 2-4 Typical MR damper (Dimock et al., 2002)

There are also medical applications which are used in commercial smart knee prosthetic, see Figure 2-5 (Carlson et al., 2001), and medical equipment (Ahmadkhanlou et al., 2009). Furthermore, MR fluid is used in industries, such as for use in the polishing and finishing products (Das et al., 2008a and 2008b; Jha and Jain, 2004; Kordonski et al., 2006).

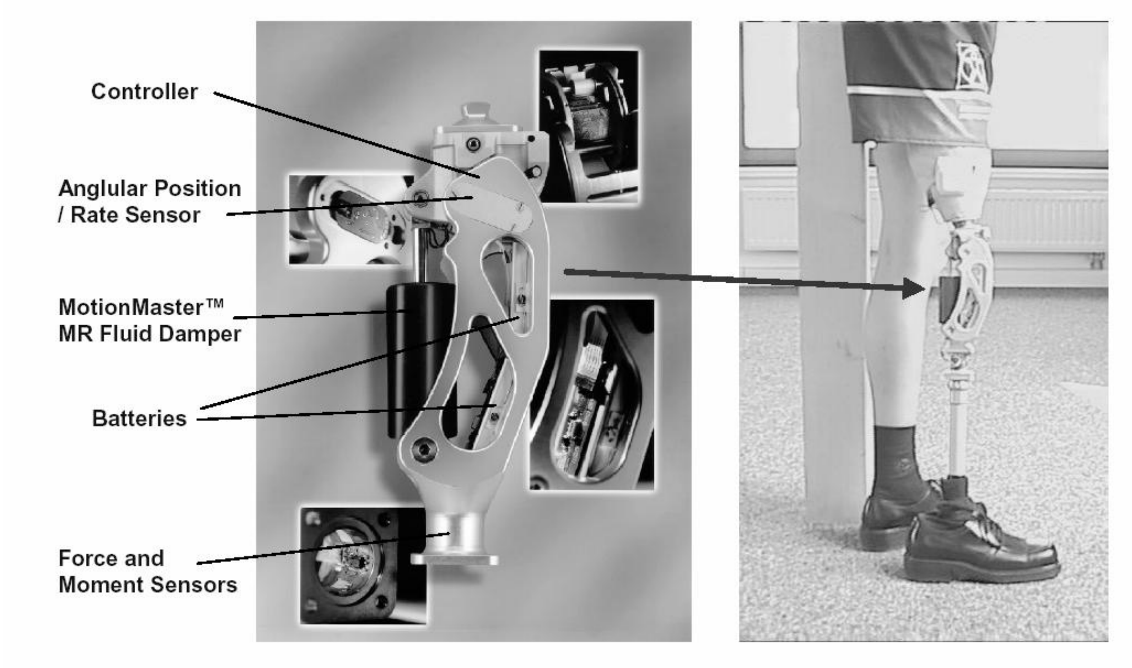

Figure 2-5 Commercial smart knee prosthesis with real-time control of MR fluid damper (Carlson et al., 2001)

2.1.3 MR fluid modes

There are three operating modes of MR fluid: valve mode (pressure mode), direct shear mode and squeeze mode, see Figure 2-6. The valve mode is the normal operating mode of MR dampers and shock absorbers, while the direct shear mode is operating mode of clutches and brakes. Some small-amplitude vibration dampers use squeeze mode (Milecki, 2001; Olabi and Grunwald, 2007).

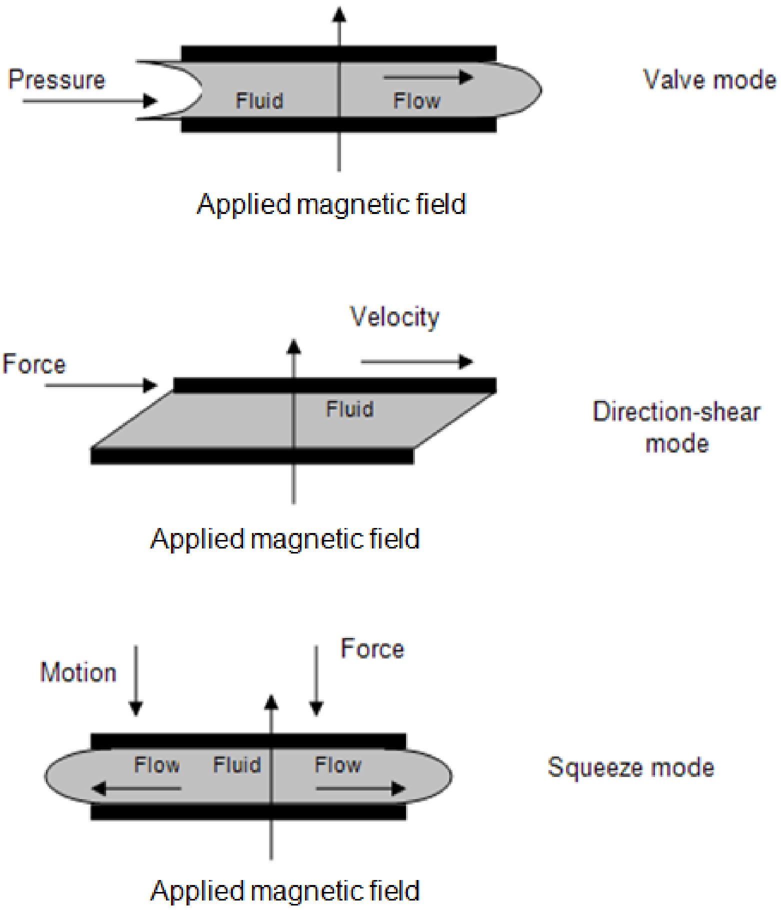

Figure 2-6 Operating modes of controllable fluids (Olabi and Grunwald, 2007)

2.1.4 MR valve design concept

The simple idea of MR valve design is "C" shape steel that carries the magnetic field generated by electrical coil, as shown in Figure 2-7. The two steel poles have been shaped to bring them closer to the MR fluid so that the magnetic field lines direction is perpendicular to the direction of the MR fluid flow. This requires that the non-magnetic material such as plastic housing, covers the two sides of the gap to keep MR fluid inside gap as illustrated in the figure. The gap shape is a flat rectangular flow channel with width *W*, length *L* and thickness *g*. The valve body is made of low carbon steel, which has specifications of high magnetic permeability and saturation. The carbon content of the steel should be less than 0.15%, such as AISI-12L14, AISI-1008, AISI-1010 and AISI-1018 steel grades that are acceptable (Lord Corporation, 1999).

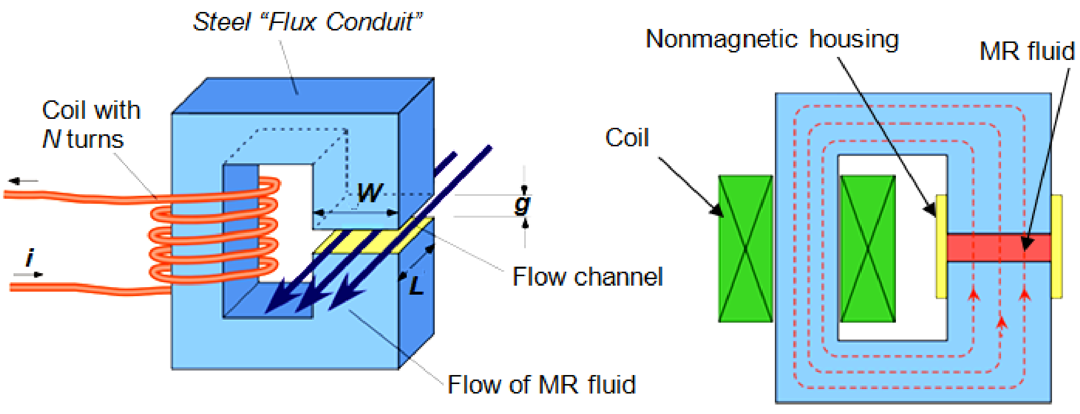

Figure 2-7 Simple idea of MR valve (Lord Corporation, 2001)

Li et al. (2003) have designed a MR valve as an axisymmetric MR fluid valve, shown in Figure 2-8. The electromagnetic coil is wound around the steel core which has bobbin shape.

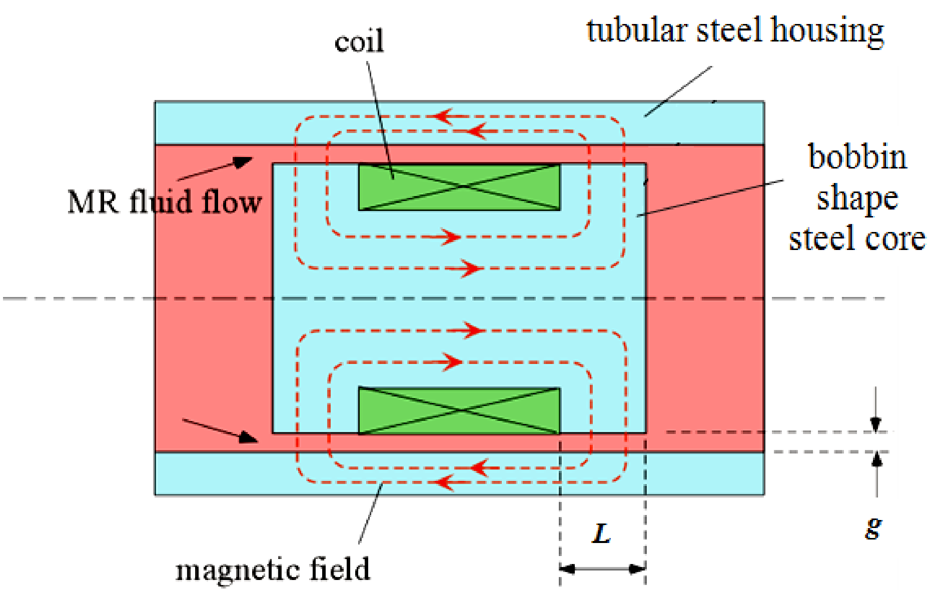

Figure 2-8 One coil annular MR valve (Lord Corporation, 2001)

MR fluid flows through the annular gap between the tubular outer housing and the steel core. When current *i* is applied to the coil with *N* turns, a magnetic field is created in the steel core, tubular outer housing and MR fluid filling annular gap as shown in Figure 2-8. Critical geometric parameters are the gap thickness *g* and the length *L*. The other design of MR valve consists of two coils of insulated copper wire wound around a cylindrical core made from a high permeability carbon steel as shown in Figure 2-9 (Yoo et al., 2005; Yoo and Wereley 2004; 2005) and (John et al., 2008). A flux return path (tubular outer housing), which is made from a high permeability carbon steel is installed around the wound core. The flux return path and the core produces an annular region between them for the MR fluid to flow.

The reason for winding of the two sets of coils in opposite direction is to provide a uniform magnetic field lines in the flow section that lies between the coils.

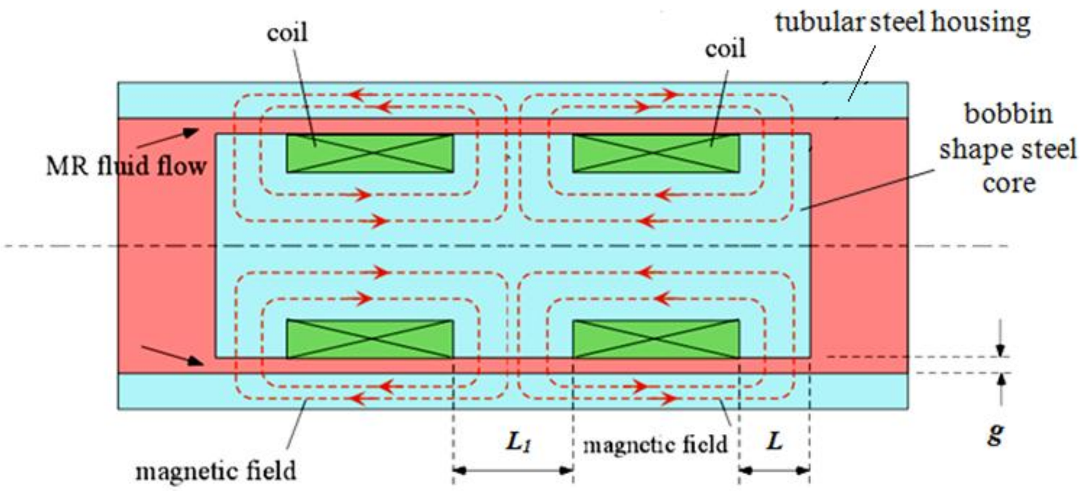

Figure 2-9 Two coils annular MR valve

There are two sets of coils that are wound in opposite directions to each other. These two sets of coils produce three different sections in the flow path where there are magnetic field lines that passes perpendicular to the direction of the MR fluid flow. These are the three active gap *g* regions of the valve of which the two are located at the ends with length *L* and other in the middle with length L_1.

2.1.5 MR fluid models

Bingham plastic model is often used to describe the behaviour of MR fluids under magnetic field. The Bingham constitutive relation can be written as (Jolly et al., 2000)

$$\tau = \pm\tau_\circ + \eta\dot{\gamma} \qquad |\tau| > |\tau_\circ| \qquad (2\text{-}1)$$

where τ is shear stress, τ_o is the yield stress, η is the viscosity and $\dot{\gamma}$ is the shear rate. The beginning of flow does not occur until the shear stress exceeds the yield stress (i.e. $\dot{\gamma} = 0$ when $\tau < \tau_o$).

Figure 2-10 shows the Bingham plastic model, which is effective in representing the magnetic field dependent on behaviour of the yield stress.

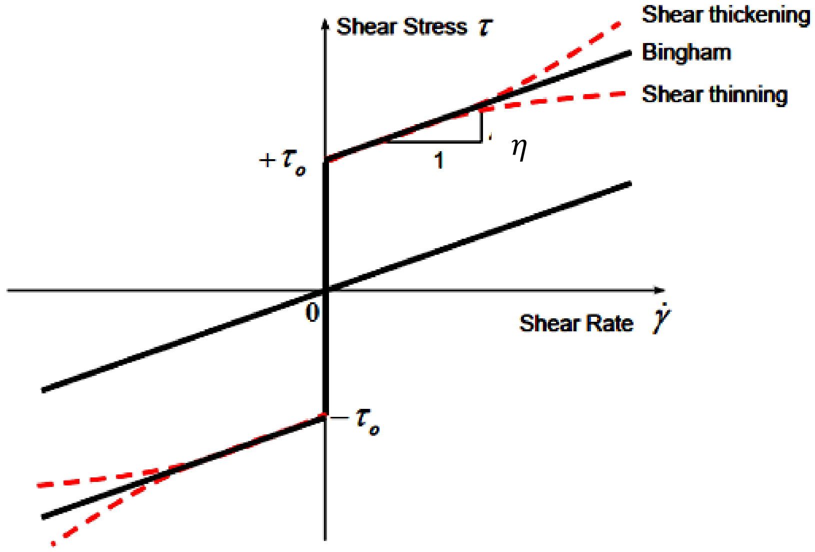

Figure 2-10 Visco-plastic models of MR fluids (Goncalves, 2005)

In the absence of a magnetic field, MR fluid behaves as a Newtonian fluid. However, when the fluid is exposed to a magnetic field a yield stress τ_o develops and the fluid behaves as a Bingham fluid (Goncalves, 2005). The Bingham model has been employed in number of models that are used to describe the behaviour of specific MR fluid devices. The simplicity of the parallel plate model and the small error justifies its use in damper models. Furthermore, parallel flow of MR fluid forms the basis for modelling of MR fluid devices operating in valve or shear mode. Rewriting the Equation (2-1) in term of the shear rate du/dy, the equation becomes (Goncalves, 2005) :

$$\tau = \pm\tau_\circ + \eta\frac{du}{dy} \qquad (2\text{-}2)$$

Figure 2-11 shows the flow of MR fluid through fixed parallel plates. It is important to note that this flow behaviour is often used to characterize the fluid flow through an MR valve.

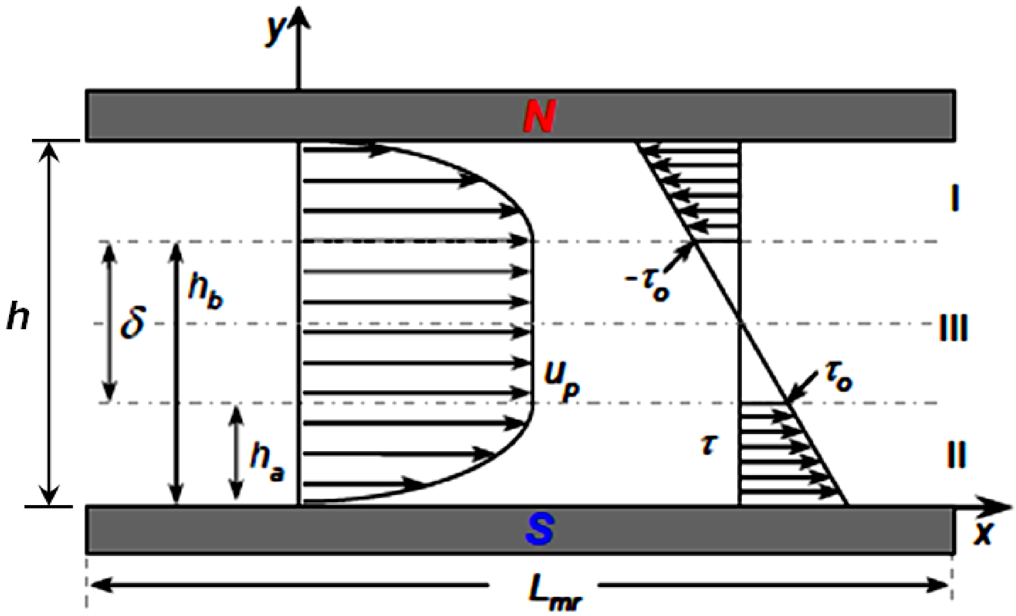

Figure 2-11 MR fluid flow through fixed parallel plates (Goncalves, 2005)

The flow behaviour depicted in Figure 2-11 can be separated into three distinct regions where *h* represents as a gap thickness, L_{mr} represents as a gap length and δ is plug thickness, as well as h_a, h_b and u_p respectively are lower limit , upper limit and velocity of MR fluid profile. In regions I and II, where the shear rate is large, the fluid flows much like the Newtonian case. In region III, however, the fluid is moving as a solid or plug through the channel. In this region, the yield stress, τ_o, has not been exceeded and thus the fluid is not being sheared.

The goal is to determine an expression for the pressure drop caused by the flow behaviour shown in Figure 2-11. Goncalves (2005) has described the MR fluid models and presented pressure drop equation which will be employed in MR valve model. The procedure outlined below begins with a reduced form of the Navier-Stokes equation for one-dimensional flow given by Nskayama and Boucher (2000).

$$\rho\left(\frac{\partial u}{\partial t} + u\,\frac{\partial u}{\partial x}\right) = \rho g - \frac{\partial p}{\partial x} + \eta\,\frac{\partial^2 u}{\partial y^2} \qquad (2\text{-}3)$$

where ρ represents as MR fluid density, g represents as gravity acceleration, u is fluid velocity and P is a fluid pressure. By enforcing boundary conditions on both the velocity u and the viscosity η, the velocity profile is found in terms of the channel geometry shown in Figure 2-11.

Assuming fully developed and horizontal flow, the momentum equation can be further reduced to

$$\frac{d^2u}{dy^2} = \frac{1}{\eta}\frac{dp}{dx} \qquad (2\text{-}4)$$

Goncalves (2005) has presented the velocity profiles in regions I and II in terms of the plug geometry as

$$u(y) = \frac{1}{2\eta}\frac{dp}{dx}y(y - 2h_a) \qquad 0 \le y \le h_a \tag{2-5}$$

$$u(y) = \frac{1}{2}\frac{dp}{dx}[(y^2 - h^2) - 2h_b\,(y - h)] \qquad h_b \le y \le h \tag{2-6}$$

From either Equation (2-5) or (2-6), the plug velocity can be found from the condition $u_I(h_a) = u_p$ or $u_{II}(h_b) = u_p$. Evaluating the velocity in region I at $y = h_a$, the plug velocity expression is found.

$$u_p = -\frac{{h_a}^2}{2\eta}\frac{dp}{dx} \tag{2-7}$$

The mean velocity through the channel can be obtained by integrating the velocity profile over the thickness of the channel.

He presented an alternative expression for the mean velocity as.

$$u_m = -\frac{1}{12\eta}\frac{dp}{dx}h^2 - \frac{1}{4\eta}h\tau_\circ + \frac{1}{3\eta h}\frac{{\tau_\circ}^3}{(dp/dx)^2} \tag{2-8}$$

for τ_o= 0, Equation (2-8) reduces to the mean velocity for the Newtonian case. Furthermore, should u_m and τ_o be known, Equation (2-8) results in a third order equation for the pressure gradient.

$$\left(\frac{dp}{dx}\right)^3 + \left(\frac{12u_m\eta}{h^2} + \frac{3\tau_\circ}{h}\right)\left(\frac{dp}{dx}\right)^2 - \frac{4{\tau_\circ}^3}{h^3} = 0 \tag{2-9}$$

with τ_o= 0, equation (2-9) reduces to the Newtonian case

$$\frac{dp_\eta}{dx} = -\frac{12u_m\eta}{h^2} \tag{2-10}$$

By considering the opposite extreme in which flow does not occur due to the formation of a plug of width h, where $\delta = h$, the critical pressure drop has been written as.

$$\frac{dp_\tau}{dx} = -\frac{2\tau_o}{h} \tag{2-11}$$

This is the lowest pressure gradient that would still generate flow between the parallel plates. Thus, in order to have flow, the following condition must be satisfied:

$$\frac{dp}{dx} \geq \frac{dp_\tau}{dx} \tag{2-12}$$

$$\frac{dp}{dx} = \frac{dp_\eta}{dx} + \frac{dp_\tau}{dx} \tag{2-13}$$

The aim in modelling stage is to observe the pressure drop ΔP in the MR valve and one way to evaluate this is by summing yield stress component ΔP_τ and the viscous component ΔP_η. Manipulating Equation (2-1) gives pressure drop (Li et al., 2003):-

$$\Delta P = \Delta P_\eta + \Delta P_\tau = \frac{12\,\eta\,Q\,L_{mr}}{wh^3} + \frac{c\,\tau_o\,L_{mr}}{h} \tag{2-14}$$

where h is gap thickness, L_{mr} is the gap length, w is width of the flow channel between the fixed poles, η is the fluid viscosity with no applied field, Q is the volumetric flow rate and τ_o is the yield stress developed in response to an applied magnetic field.

The parameter c has a value ranging from a maximum value of 3 (for $\Delta P_\tau/\Delta P_\eta$ greater than 100) to a minimum value of 2 (for $\Delta P_\tau/\Delta P_\eta$ less than 1).

2.2 Mathematical model of flow in MR valve

The foundation of simulations is mathematical modelling of the MR valves. The modelling of the proposed developed MR valve is based on the assumption that the fluid flow resistance induced by the valve is the summation of the fluid flow resistances induced by the circular disk channels and the annular channels.

2.2.1 Modelling of MR fluid flow in a circular disk channel

The working model of the MR fluid flow in the circular disk channels (radial gap) is shown in Figure 2-12. The radial flow resistance channel has thickness *g,* which is equal to the distance between the two circular disks. The MR fluid flows into the radial resistance gap through the central hole of the valve core. The pressure of the MR fluid in the MR valve drops along the

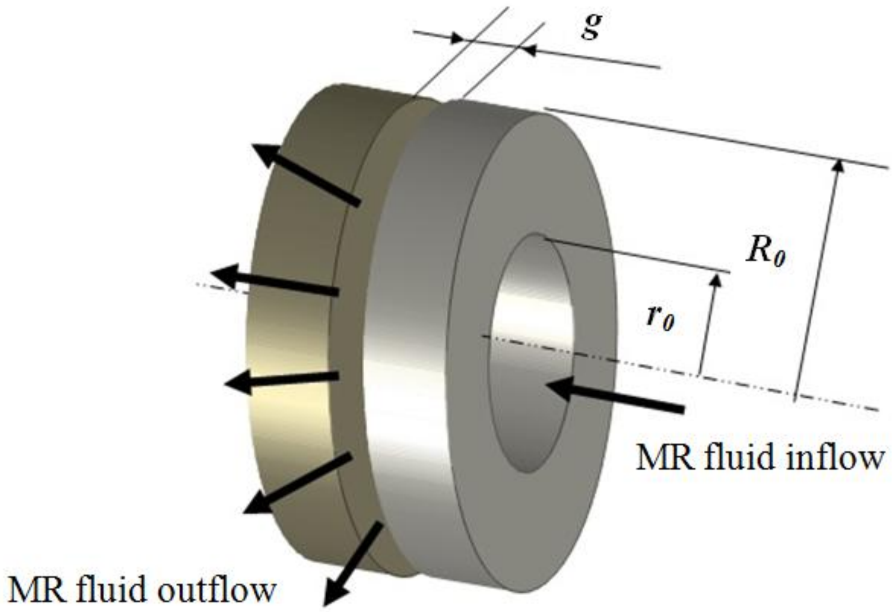

Figure 2-12 Modelling of MR fluid flow in radial flow gaps