HYBRID CFD-NNARX MODELLING OF SINGLE MRF VALVE FOR VISUAL SERVOING

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HYBRID CFD-NNARX MODELLING OF SINGLE MRF VALVE FOR VISUAL SERVOING

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LIST OF ABBREVIATIONS

ANN	Artificial Neural Network
CAD	Computer Aided Drawing
CFD	Computational Fluid Dynamic
EHA	Electro-Hydraulic Actuator
EHSS	Electro-Hydraulic Servo System
FVM	Finite Volume Method
LQR	Linear-Quadratic Regulator
MRF	Magneto rheological fluid
NNARX	Neural Network AutoRegressive with eXogenous input
PDE	Partial Differential Equation
PID	Proportional Integral Derivative
PWM	Pulse Width Modulation
SISO	Single Input Single Output
UDF	User Defined Function

LIST OF SYMBOLS

I	Current (A)
τ	Shear stress (Pa)
τ_0	Yield shear stress (Pa)
H	Magnetic field strength (A/m)
η_∞	Nominal viscosity (Pa. s)
$\dot{\gamma}$	Shear rate (s^{-1})
η_α	Apparent viscosity (Pa. s)
Q	Flow rate (cm^3/sec)
$\dot{\gamma}_0$	Critical yield shear strain rate
B	Magnetic flux density (Tesla)
U	Velocity of MR fluid (cm/sec)
U_{mean}	Average velocity of MR fluid (cm/sec)
K_p	Coefficients for the proportional
K_i	Coefficients for the integral
K_d	Coefficients for the derivative
K_{pu}	Critical gain
P_u	Ultimate period (second)
R_e	Reynolds number
P	Fluid pressure (Pa)
f	Frequency (Hz)
t	Time (s)
L	Length (mm)

PERMODELAN HIBRID CFD-NNARX BAGI INJAP MRF TUNGGAL UNTUK SERVO VISUAL

ABSTRAK

Penggerak Bendalir Reologi Magnet (MRF) muncul sebagai satu sistem yang berpotensi bagi menggantikan servo electro-hidraulik. Pemodelan bagi injap penting dalam membangunkan sistem kawalan yang optimum, tetapi pengetahuan kelakuan bendalir dalam saluran injap sangat terhad. Objektif kajian ini adalah untuk membangunkan model pengerak MRF menggunakan pendekatan sistem pengenalanpasti di mana Pengkomputeran Dinamik Bendalir (CFD) digunakan sebagai input. Model kemudiannya digunakan untuk merekabentuk sistem kawalan gelung tertutup untuk penggerak MRF. Untuk mencapai objektif, model 3-Dimensi CFD perlu dibangunkan, dan analisis keadaan mantap telah dijalankan untuk mengkaji kelakuan bendalir dalam saluran. Seterusnya, analisis fana dengan input dinamik dilakukan untuk mengkaji hubungan antara input dengan jumlah kadar aliran semasa sebagai output. Autoregresif rangkaian neural masukan luar (NNARX) menggunakan data daripada CFD untuk mengenal pasti model dinamik injap MRF. Hasilnya, simulasi CFD dan model dinamik sepakat dengan hasil eksperimen dengan ralat kurang daripada 3%. Halaju bendalir di dalam injap berkurangan sebanyak 85% apabila arus berubah daripada 0 ke 0.8A. Model hibrid CFD-NNARX menunjukkan sisihan kecil dengan hasil purata ralat eksperimen 4%. Kesimpulannya, Hibrid CFD-NNARX telah terbukti berguna dalam permodelan penggerak MRF. Sumbangan utama penyelidikan ini adalah model penggerak MRF yang boleh digunakan sebagai input dalam proses rekabentuk pengawal penggerak MRF.

HYBRID CFD-NNARX MODELLING OF SINGLE MRF VALVE FOR VISUAL SERVOING

ABSTRACT

Magnetorheological fluid (MRF) actuator emerged in the last decade as a potential system to replace electro-hydraulic servo system in precision applications. A complete closed-loop control system is necessary to support the accuracy of the system. Modelling of the valve is a crucial task in developing an optimal control system for the valve, but the knowledge of fluid behaviour inside the valve channel remains scarce. This research aims to develop a plant model of MRF actuator using the system identification approach, where the Computational Fluid Dynamics (CFD) result is used as an input. The plant model is then used to design a closed-loop control system for the MRF actuator. To achieve this objective, a 3D CFD model was developed, and a steady state analysis was run to study fluid behaviours in the channel. Transient analysis with dynamic input was further performed to study the correlation between the current input and the volume flow rate as an output. Neural network nonlinear autoregressive network with exogenous inputs (NNARX) used data from the CFD to identify the plant model of an MRF valve. The result acquired from the CFD simulation and plant model gave good agreement with the experimental result with an error of less than 3%. The velocity in the MRF valve reduced 85% when the current varied from 0 to 0.8A. The hybrid CFD-NNARX model shows a small deviation from the experimental result with an average error of 4%. As a conclusion, the hybrid CFD-NNARX has been proven useful in modelling the MRF actuator. The main contribution of this work is the plant model of an MRF actuator, which can be utilised as an input in controller design process of MRF actuator.

CHAPTER ONE
INTRODUCTION

1.1 Overview

This chapter describes the background of the research, including the motivation and significance of this work. The problem statement section provides a technical description of the specific issue. The objectives and approaches to achieve the objectives are also presented. Then, the chapter elaborates the scope of work that determines the boundary of the research. Finally, the chapter concludes the document outline.

1.2 Background

Accurate and precision positioning systems have emerged as a vital requirement in the industry (Wonohadidjojo *et al.*, 2013). Motorised actuators are popular choices in developing a positioning system over several decades. However, in a high load application, a motorised actuator is less efficient compared to a hydraulic actuator (Guo *et al.*, 2015a). To this extent, an electro-hydraulic system has been introduced by many practitioners to answer the limitation of the motorised actuator system when a high load is needed (Guo *et al.*, 2015a; Le-Hanh *et al.*, 2009; Lin, 2011). The accuracy of the electro-hydraulic system is ensured by utilising a servo valve that is used to control the displacement of the cylinder. A conventional hydraulic control valve consists of a spool, inside which acts as a control mechanism. This spool is moved by a solenoid, and the speed of spool is determined by the current induced in the solenoid (Kang *et al.*, 2008). It is clear that proper control of the servo valve will help improve the accuracy and precision of a hydraulic positioning system.

The spool has introduced difficulty in controlling the valve due to friction with the valve body. Therefore, the magnetorheological fluid (MRF) valve was designed and has proven to control fluid flow (Grunwald & Olabi, 2008; Imaduddin *et al.*, 2014; Moon *et al.*, 2011; Hadadian *et al.*, 2014). The MRF valve has successfully eliminated the use of a spool to control fluid flow by manipulating the MRF rheological properties using a magnetic field. The MRF is considered a smart material where its state might change from liquid to solid in milliseconds with the presence of magnetic field (Ekwebelam & See, 2009). The invention of the MRF valve potentially accelerates the development of an accurate positioning system. Even though the MRF valve was successfully designed to control the direction of the MRF, the valve is limited to simple geometry such as a straight channel. However, if the channel's is complex, for example having a curvature, it becomes difficult for the MRF valve to regulate due to a lack of understanding fluid flow behaviour. Thus, the design process requires knowledge of fluid flow inside the valve while a magnetic field is applied.

One way to analyse fluid flow behaviour is by using the CFD, which is the acronym for Computational Fluid Dynamics. CFD is considered as a simulation tool that uses a powerful computer and applied mathematics to model fluid flow situations for the prediction of heat, mass, and momentum transfer, as well as the optimal design of industrial processes (Gurreri *et al.*, 2016; Shirazi *et al.*, 2016). Recently, CFD has been used widely in solving problems related to material engineering, especially smart materials such as MRF (Gedik *et al.*, 2012; Parlak & Engin, 2012). Besides that, CFD also has the capability to model the transient of a fluid system. Thus, CFD data shown by Dobrev & Massouh (2011), Meng *et al.* (2009), and

Zerihun-Desta *et al.* (2004) is useful in modelling plant model through system identification approaches.

System identification has more advantages in modelling a nonlinear system than an analytical method (Schoukens *et al.*, 2015), as the analytical method of a system modelling requires a complex mathematical equation and sometimes leads to assumptions that reduce the accuracy of the plant model (Paduart *et al.*, 2010). In contrast, system identification attempts to develop a plant model using input-output data from an experiment. Increasing the complexity of the system to be a model makes the conventional system identification method fail to develop an accurate plant model (Xie *et al.*, 2013). Thus, an artificial method is embedded into the system identification to cope with the nonlinearity effect (Romero-Ugalde *et al.*, 2013). Artificial Neural Network (ANN) is a popular method adopted by many researchers in solving the issue of nonlinearity in system modelling. Neural network offers the capability to develop a nonlinear function, which is important in predicting nonlinear behaviour in the system. A Neural network that is autoregressive with exogenous input (NNARX) is an example of the ANN method used in system modelling. This technique is a combination between conventional system identification models, namely autoregressive with exogenous terms (ARX) and ANN. The NNARX model has been applied to many industrial applications and has shown more advantages than other methods in several cases (Deng, 2013; Folgheraiter, 2016; Janakiraman *et al.*, 2013; Xie *et al.*, 2013).

In general, this research is important for the future development of an optimal MRF valve. When the model of the MRF valve is validated, its geometrical optimisation can be done with less experimental works. Nevertheless, knowledge in fluid particle interaction is important, but till now, it is still hardly reported in the literature. Within a proven method in the numerical model and experimental work, a more detailed mathematical model that is more accurate on the particle was able to be developed by the researcher. The particle model lead to another finding on suspension particle and finally improved human knowledge on the particle.

1.3 Problem Statement

Electro-hydraulic actuator (EHA) is extensively used in the positioning system, but the accuracy is low due to its complexity in controlling the spool inside the valve. Salloom and Samad (2012) and Imaduddin *et al.* (2014) developed an MRF valve that worked without a spool, but fluid behaviour in MRF valves have yet to be understood. Due to a lack in knowledge about MRF flow, the response of the valve is difficult to predict and the development of an optimal control system becomes slow. Even though Omidbeygi and Hashemabadi (2013) solved the MRF fluid flow using an analytical solution, it is limited to simple geometry and strictly followed a 2D flow assumption.

The plant model of the valve is an important input to design an optimal controller and commonly developed using the analytical or system identification approach (Wang & Gordaninejad, 2007; Khalid *et al.*, 2014). When a magnetic field is applied to the MRF valve, the MRF response is difficult to model analytically and the system identification becomes a better choice for modelling purposes. System identification requires an input-output data, but in the design stage, the data is not yet collected so that the CFD approach can be used to replicate an experiment for the data collection process. Thus, the modelling of the valve requires a hybrid between the CFD and system identification.

As verification is compulsory in the plant model development process, the MRF actuator requires feedback to measure the response. Displacement sensor is normally used to give feedback to the controller, and most of the displacement sensors are installed at the actuator because it reduces the measurement reliability due to vibration. Thus, a noncontact measurement system such as a vision-based sensor is needed. However, because there is still no literature that reports that the vision-based sensor is used to work with the MRF actuator, the development of a vison-based feedback system for the MRF actuator is needed.

1.4 Research Objective

The aim of this research is to develop the plant model of a single MRF valve using hybrid CFD-NNARX. To fulfil this purpose, several objectives were defined as the following:

1. To evaluate the steady-state and transient flow behaviour of MRF in a curve valve channel using the CFD approach;
2. To develop a plant model of the MRF valve using the hybrid CFD-NNARX identification method;
3. To develop an MRF actuator embedded with the robust vision-based feedback for model validation; and
4. To analyse the hybrid CFD-NNARX model performance using a visual servoing MRF actuator.

1.5 Scope of Research

This work is divided into two main stages: experimental and modelling. In the experimental stage, a complete closed-loop magnetorheological linear actuator was developed and tested. The experimental data was used in the validation process for the CFD and neural network models. Meanwhile, in the modelling stages, a CFD model for the MRF valve was developed and the results were used as raw data to develop a plant model for the MRF valve.

The extent of this present work to develop a nonlinear plant model for the single MR fluid valve. The plant model is developed using the hybrid CFD-NNARX, which is a combination of numerical modelling and a system identification approach. This work covers the numerical modelling of fluid flow characteristic in a single MRF valve using the CFD method. A viscosity model was developed specifically by combining the results from the finite element analysis of magnetic field in the valve.

The model was then validated with the experimental data. Next is the development of the closed-loop MRF linear actuator. A machine vision system was also developed to work as visual feedback. A PID controller was designed to make the MRF linear actuator performance better. It was tuned to test whether the plant model is capable of searching for an optimal controller for the real MRF system.

1.6 Thesis Outline

The thesis is presented in five chapters, including an introduction, literature review, methodology, results and discussion, and finally the conclusion. Chapter One consists of the background of the study, research objectives, and thesis outline. Chapter Two consists of the literature review, where previous works conducted by other researchers regarding magnetorheological valve, CFD, and NNARX are examined and discussed.

Chapter Three describes the methodology used in this study, including the development of the magnetorheological linear actuator and the CFD modelling.

Chapter Four presents the results, as well as the discussion of the outcomes. Chapter Five presents the conclusion and recommendations of the present work.

CHAPTER TWO
LITERATURE REVIEW

2.1 Overview

A literature survey on previous work was conducted to search for a research gap. Firstly, the importance and current art of electrohydraulic actuator are review. This first section also includes a brief explanation on MRF and the valve. The second section deals with the CFD analysis of the MRF. Thirdly the review focuses on CFD application in system identification. Next, the literatures expand into vision-based positioning system. The final section focuses on the use of machine vision as a feedback for measuring displacement. This chapter was ordered to follow the objective this research as mentioned in Chapter 1.

2.2 Conventional Electro Hydraulic System

The Electro-Hydraulic Servo System (EHSS) is widely used in industrial and machinery settings for high-performance position tracking applications. The EHSS system is capable of generating high forces with fast response time and offers great durability, particular by for heavy engineering systems with a compact size and design (Ahn *et al.*, 2002; Guo *et al.*, 2015a; Lin, 2011). The EHSS usually consists of a double-acting cylinder actuator driven by a proportional directional control valve connected to a hydraulic pressure unit. It has proven to be a promising choice for various mobile and high-performance applications due to its high power to weight ratio, good dynamic performance, and its ability to tolerate abrupt and aggressive loadings. This type of system can generate very high forces and has a very high power to weight ratio compared to its electrical counterparts. This characteristic makes the

EHSS ideal for various high-performance applications, and it is widely utilised in aircraft control, machine tools and manufacturing, excavating, and automotive industries.

Figure 2.1 presents a complete example of the EHSS. The hydraulic system is used to drive a cylinder in controllable position and speed. It consists of the power source, servo valve, and actuator. The power source system has a pump to push the fluid at a certain level of pressure and flow rate. The pump used depends on the power required and the type of fluid. Positive displacement pumps are commonly used as opposed to non-positive displacement pumps. Positive displacement pumps such as gears, vanes, and screws for rotary type, and pistons for reciprocating type offers high pressure which is important for hydraulic applications.

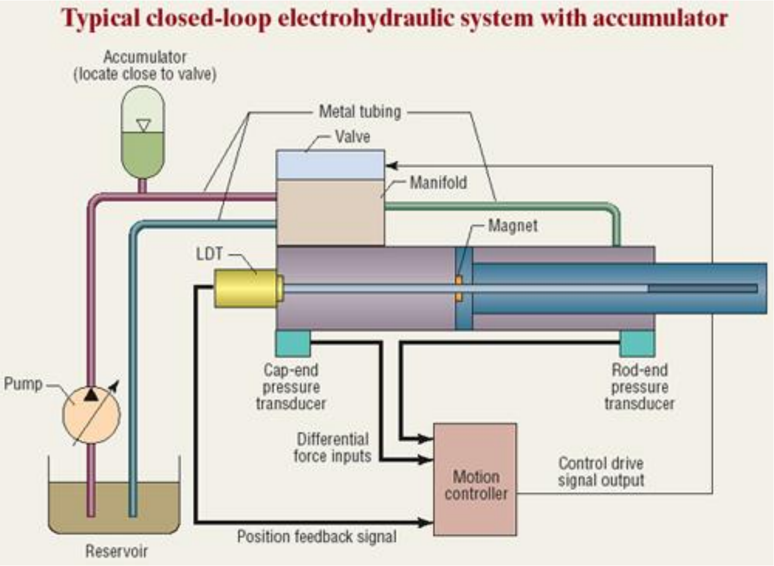


Figure 2.1 Electro-hydraulic system (Peter-Nachtwey, 2006)

The pump pushes the fluid to the actuator from the reservoir through the valve. The valve acts as a control device to manipulate the direction and the pressure of the fluid. If the extended mode is required, the fluid will be redirected to the rear chamber and the pistons start to move. The sensor will detect the position of the piston and calculate the velocity. The motion controller can use the displacement and speed information to make a decision as to how best to control the motion accurately. The decision is converted into an electrical signal then sent to the servo valve. The servo valve accepts the signal which starts to change the flow pressure and flow direction according to the signal.

The EHSS is controlled by the servo valve to manipulate the pressure and flow direction according to input desired by the operator. The servo valve shown in Figure 2.2 consists of the spool inside the valve and the spool motion controlled by the magnetic field generated by the solenoid coil. In practice, the control system was developed to control the position or the speed of the spool. This method requires a highly complex control system due to the nonlinearity introduced by the friction occurring between the spool and the channel wall. This causes the controller to become more complex sometimes rendering its application impractical in industrial applications.

Ghazali *et al.* (2012) presented an optimal control for tracking discrete-time non-minimum phase of an electro-hydraulic actuator (EHA) system by adopting a combination of feedback and feedforward controller. The proposed controller was performed in simulation and experimental studies where the EHA system is represented in a discrete-time model. This is obtained using the system identification technique where a linear-quadratic regulator (LQR) is firstly designed as a feedback controller, and a feed forward controller is then proposed to eliminate the phase error resulting from the LQR controller during tracking control. Similar approaches were shown by Chen and Lian (2011) and Liu *et al.* (2014) but in different applications. The feed forward controller was developed by implementing the zero phase error tracking control (ZPETC) technique in which the main difficulty arises from the no minimum phase system with no stable inverse. The result obtained from the study showed that the controller offers good performance in reducing phase and gain error that usually occurs in positioning or tracking systems.

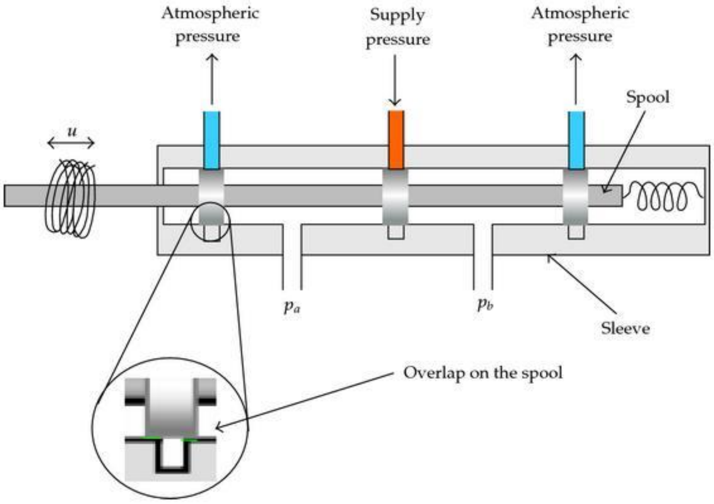


Figure 2.2 Conventional servo valve illustration (Valdiero *et al.*, 2011)

In the same direction, Tivay *et al.* (2014) developed a controller for the valve to optimise the energy used in the system. The optimal controller concept was applied and showed good performance in minimising energy. The torque performance also improved better by controlling the valve as shown by Wang *et al.* (2015a). The positioning of the cylinder showed a significant improvement when the H∞ controller was used to drive the servo valve. The pioneering work was done by Guo *et al.* (2015b) showed that using the H∞ controller possibly reduced the tracking error of the cylinder due to the friction effect. Some researchers also used intelligent controllers for the servo valve.

Wonohadidjojo *et al.* (2013) utilised the couple fuzzy and particle swarm optimisation method to develop a position control for the EHSS system. The controller successfully determined the opening range of orifice in the servo valve. The fuzzy controller was also used by Renn and Tsai (2005) when implementing a switching control for the solenoid valve in hydraulic press application. The fuzzy controller successfully controlled the force acting on the workpiece during the press process. Similar works examined the use of the fuzzy based controller in the EHSS system (Le-Hanh *et al.*, 2009; Songshan *et al.*, 2015; Zheng *et al.*, 2009).

Other than a fuzzy controller, the neural network also offers advantages in designing the controller for the EHSS system. In missile tracking applications, reliability is a very important factor since it relates to human safety. EHSS shows good performance even in high precision applications. However, the controller needs to be sufficiently reliable to run the system properly as shown by Cao *et al.* (2006). Their study used a neural network coupled with the sliding mode control method to develop a precise control system for missile tracking. Faults model of the valve is important to determine the reliability of the EHSS performance. Huang *et al.* (2006) used genetic algorithms and neural networks as tools to study the fault behaviour in servo valve. The model significantly contributed to predicting the valve model and indirectly improved the reliability of the EHSS system. This further proved that the neural networks method is widely used in developing a controller in the EHSS system. Other clear examples of neural networks implementation in EHSS can be seen in Kang *et al.* (2008) and Kilic *et al.* (2014). The literature clearly shows that the servo valve controller remains a critical issue to improve the overall performance of EHSS. Servo valve controller is required to be fast in response, disturbance rejection, less steady state and tracking error. Searching for these criteria remain a critical issue in servo valve controller design (Kang *et al.*, 2008). To date, various controllers have been developed by researchers either using conventional methods or intelligent approaches. Besides the controller of the valve, the power pump and pressure relief valve have also become subjects of interest for researchers in optimising EHSS operations.

The pump system is a major element to ensure the EHSS is working as expected. Issues arise when the power or energy consumed by the pump must be minimal as possible. Many dimensions have been explored by researchers regarding the pump such as a controller, mechanical component, and also the electrical system. The comprehensive review by Quan *et al.* (2014) shows various work on direct pump control technology embedded in the EHSS system. The direct pump control technology aims to minimise energy used to manipulate the EHSS actuator. The argument that a proper pump controller saves energy is supported by other researchers (Chu *et al.*, 2006; Hong & Doh, 2004). Ho & Ahn (2010) studied the pump's role for improving the transmission line using an accumulator. However, the study of the pump is still in its early stages compared to the study of the valve due to the widely held argument that improving valve technology will generally optimise the pump system.

Hős *et al.* (2014; 2015) formulated a nonlinear plant model of a relief valve in the stage form. According to the results, the opening time of the valve is linearly related to the dimensionless parameter given by the ratio of orifice length to the radius. Liu and Jiang (2014) developed plant models of a spring loaded pressure relief valve with computational fluid dynamics and valve plant modelling. Athanasatos and Costopoulos (2012) and Dransfield and Teo (1979) studied the dynamics of a pilot operated pressure relief valve using the Bond graph simulation technique. The governing equations of the system were derived from the model. Song *et al.* (2013) and Wenbing *et al.* (2012) developed a relatively simple and accurate model to solve the dynamical behaviour of a pressure reducing valve. Sizing is the most important component in selecting the right pressure relief valve for the circuit assuring the reliable safety of the system. Nowadays, sizing is achieved with software available on the market and provided by manufacturers. It is important to understand what is behind the software and to look into the formulas on which these calculations are based. It is also important that relief valves be selected by the operators with detailed knowledge of all the pressure-relieving requirements of the system to be protected. The circuit designer must be aware of what is available on the market in order to select the right valve for the correct application to assure a safe hydraulic system.

Accuracy, stiffness, and controllability are major factors when designing a linear actuator. The electro-hydraulic system offers several advantages such as high stiffness and applicability to many working environments as compared to the electrical motor. However, the system suffers from being bulky in size and complexity in controlling the motion. The main factor attributed to this drawback is the hydraulic valve used to control the fluid direction. The valve is controlled by supplying a current to the armature coil and the magnetic field generates forces and pushes the spool inside the valve. Utilising a spool as a control mechanism introduces friction leading to increased complexity in controlling the flow. Answering this drawback, this research seeks a new solution for designing the hydraulic valve. Due to the ability to change from liquid to viscoelastic states, the MRF is considered an appropriate candidate to explore its potential as a valve. Although a working MRF valve has been invented, there is little research on the use of this valve in industrial applications.

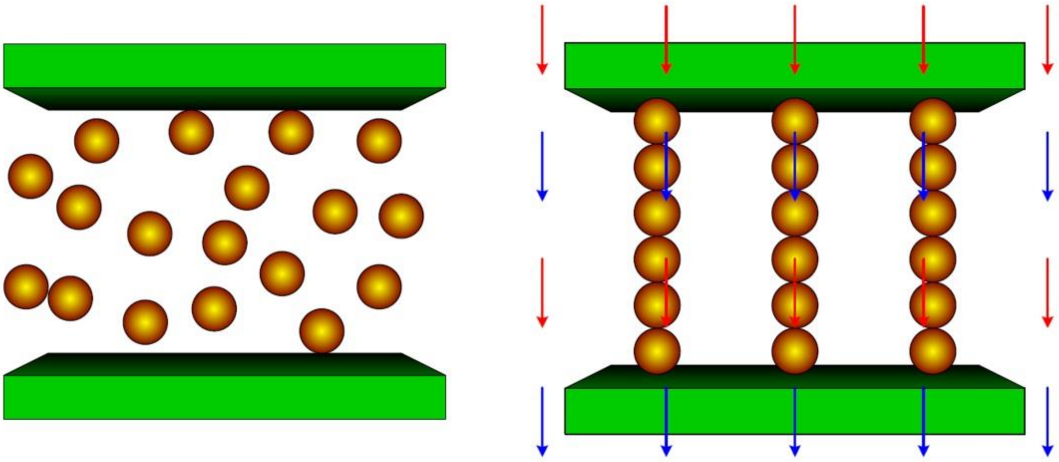
The main issue that emerges is that the valve is still in a single mode with the ability to control only one flow direction at one time. To reduce complexity, a compact MRF was designed to control the fluid direction in a single geometry. However, this compact valve is only designed to meet a reduction in size. The plant model and the flow of the valve remain major questions for the valve to be used in real applications. There is therefore need to understand the fluid flow inside the valve as a means to better design the valve controller. The plant model for this valve has never been developed presenting an urgent need to model this compact valve to increase the possibility of its use in industrial applications.

2.3 Magneto-Rheological Fluid

MRF is categorised as intelligent material due to it rheological properties capable of changing from the Newtonian fluid into Bingham plastic with the presence of a magnetic field (Ashtiani & Hashemabadi, 2015; Zhou *et al.*, 2015). The magnetic field acts as a power source for the fluid where the yield stress increases with increases in the magnetic field. The fluid was first introduced by Rabinow in late 1949 as an alternative to the electro-rheological fluid. In principle, MRF consists of iron particles suspended in mineral or silicon oil. The iron particle size lie in between 5-10 micron (Bica *et al.*, 2015). The magneto-rheological effect is shown in Figure 2.3.

In the absence of magnetic field, the iron particles are distributed homogeneously in the continuous silicon oil with Brownian motion. In this condition, the rheology can be assumed as Newtonian fluid (Sherman *et al.*, 2015). The viscosity of the fluid is influenced by the volume fraction of the iron particle with suspension media. To avoid locomotion in the particle due to particle-particle interaction, the iron particle was coated with the Nanolayer polymer lithium grease (Dong *et al.*, 2012;

Iglesias *et al.*, 2012; Yamanaka *et al.*, 2012). This layer of coating is important to maintain the distribution of the particle in the media with minimal sedimentation effect. The fluid is also stable in a wide range of temperatures from 10 to 140 degree. These properties render the fluid applicable for numerous industrial applications (Park *et al.*, 2009).



(a) Without Magnetic Field

(b)With Magnetic Field

Figure 2.3 Magneto-rheological working principle (Truong & Anh, 2012)

The rheological properties of MRF gradually changed in the presence of the magnetic field. Ekwebelam and See (2009) explained this physical phenomenon of the fluid using a spherical particle model. The magnetic field induces the force into the iron particle, and the particle starts to align to produce resistance to any external force. Peng *et al.* (2009) and Yongzhi *et al.* (2011) showed the mechanism of the particle with the presence of the magnetic field using the Monte Carlo method. The iron particle starts to develop a chain and cluster in the fluid domain. The chain holds the particle together and the holding force depends on magnetic field magnitude. The force provides resistance to the fluid flow and increases its shear force to break the chain. Thus, with increasing magnetic field, the yield stress of the fluid is increased.

The three modes of MRF are the shear mode, valve mode, and squeeze mode as shown in Figure 2.4 (Yazid *et al.*, 2014). In shear mode operation, one of both of the surface is moving, and the magnetic field is perpendicular to the surface. Shear mode is used when the application relates to torque as an output such as in a braking system. When the magnetic field is present, the fluid tends to bind together and resist any motion of the surface.

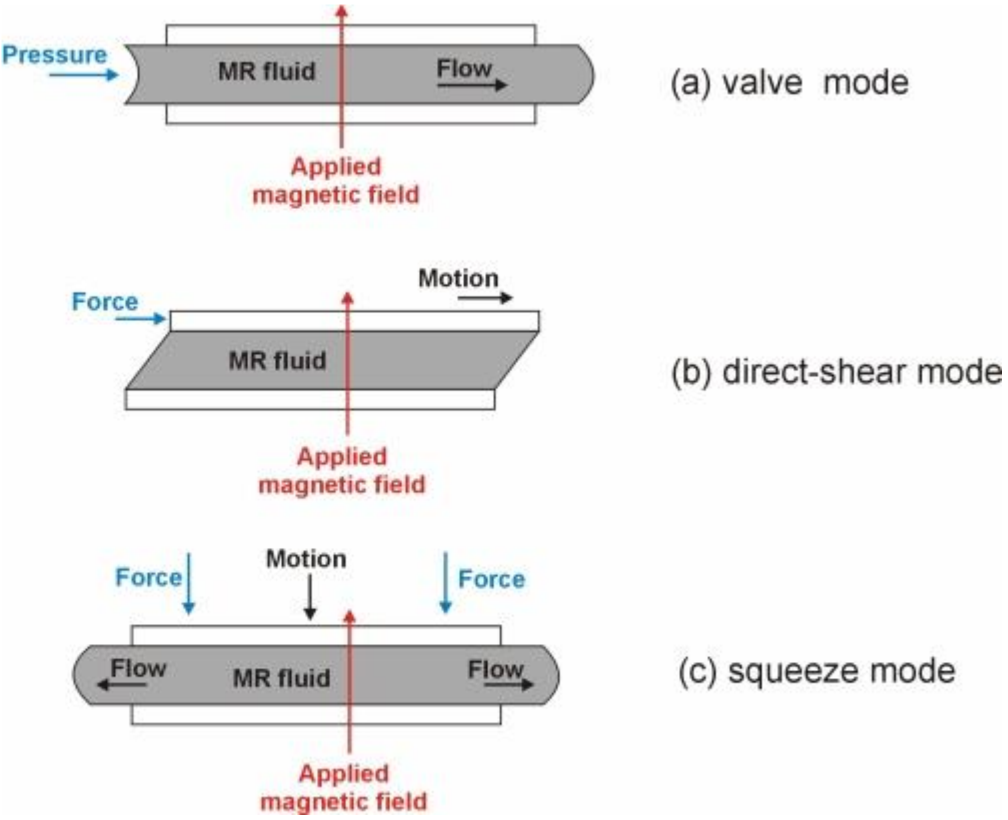


Figure 2.4 Magneto-rheological modes of operation (Mazlan *et al.*, 2009)

This property can be applied in controlling the torque continuously (Nguyen *et al.*, 2014). In valve mode operation, both surfaces are fixed and the fluid moves by external pressure. In this mode, the fluid starts to resist the flow and reduces the pressure.

Similar to shear mode, the chain creates resistance and the pressure is used to break the chain. In the squeeze mode, any or both surfaces move in the direction of the magnetic field. With the presence of a magnetic field, the particles come closer together and create a displacement to the surface. Squeeze mode is commonly used in developing acoustic transducers.

2.3.1 MRF Device

Because the state of MRF materials can be controlled by the strength of an applied magnetic field, it is useful in applications where variable performance is desired. Microprocessors, sensor technologies, and increasing electronic content and processing speeds have created real-time control possibilities of smart systems used by MRF devices. With different modes of operation, the MRF shows many potential applications in industry. The MRF technology offers several advantages compared to conventional mechanical devices in terms of controllability (Bossis *et al.,* 2002; Nguyen *et al.,* 2014; Russo *et al.,* 2015).Perhaps the most popular application of MRF in the industry is the linear damper system as shown in Figure 2.5. This system was designed to absorb vibration with wide range frequency (Zalewski *et al.,* 2014). The capability to change the stiffness of the fluid inside the damper renders this MRF valve useful in many industrial applications even in heavy vehicle design such as truck suspension (Orečný *et al.,* 2014; Tsampardoukas *et al.,* 2008).

In the automotive field, this type of damper is useful for providing a smooth driving experience. Boada *et al.* (2011), Dominguez *et al.* (2008) and Raju *et al.* (2015) all worked on designing and controlling the MRF damper to suit automotive applications. Their prototypes prove that the MRF damper is able to reduce the effect of vibration even when random excitation signal emerged. Their works indicate that the MRF damper can be controlled intelligently to overcome the effect of vibration due to uncertainty in road terrain. The MRF damper was also tested on a larger scale when it was applied to reduce the effects of an earthquake in a building (Kim *et al.*, 2015; Li *et al.*, 2013; Uz & Hadi, 2014; Yang *et al.*, 2013). Besides buildings, bridge designs also included MRF damper technology. Several researchers explored the potential of the MRF damper for improving bridge design (Erkus *et al.*, 2002; Luu *et al.*, 2014; Ok *et al.*, 2007; Yang *et al.*, 2011). The critical issue is when the high-speed wind effect was considered a factor in design. Passive dampers conventionally used nowadays are no longer efficient to cope with uneven climate change. Thus, there is a need to exploit an intelligent material such as MRF to design bridges. Figure 2.5 shows the MRF damper design which is used in industry and accepted as a future trend in damper technology. Besides the valve, MRF also has an important contribution to braking system design.

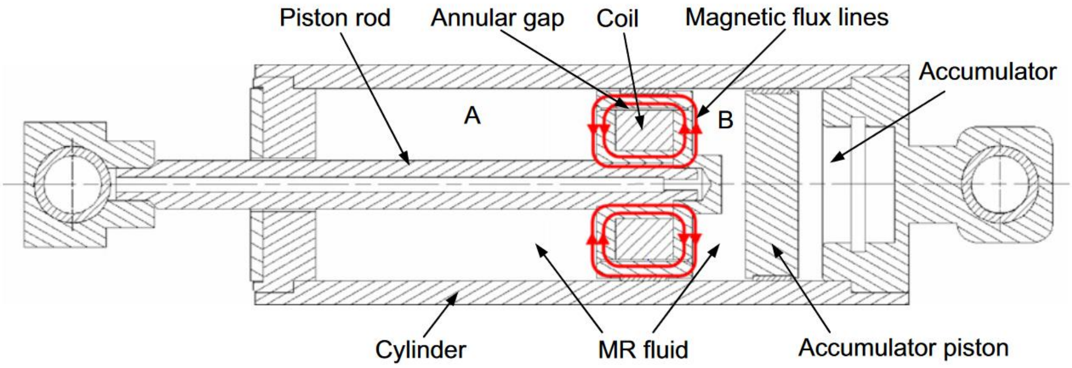


Figure 2.5 MRF damper system (Çeşmeci & Engin 2010)

Braking systems nowadays suffer from several drawbacks such as high friction, wear, jerking, and overheating. These issues arise due to the direct contact between the disc brake and the brake pad. To overcome this problem, new braking concepts were introduced utilising an MRF as an active element (Park *et al.*, 2006). In the case of braking, the fluid was placed in between the disc plate and the shaft as shown in Figure 2.6. Karakoc *et al.* (2008) and Park *et al.* (2008) developed a numerical model for an MRF braking system in order to optimise the geometrical and electrical design. An optimal parameter gained from a numerical was validated using a developed prototype and showed good agreement. Further the numerical model was used to study the behaviour of the braking system. Before that, Bica (2004), Huang *et al.*, (2002) and Li and Du, (2003) designed the MRF braking system and studied the performance of the brake experimentally.

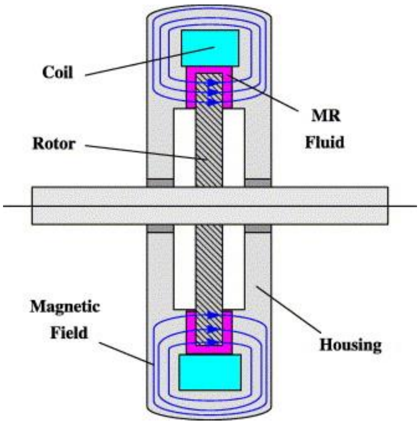


Figure 2.6 Magneto-rheological brake (Thanh & Ahn, 2006)

However, no numerical model was developed at that stage. The braking system also captured the interest of the haptic community in order to improve the efficiency of devices (Demersseman *et al.*, 2008). Shiao and Nguyen (2014) proved that the MRF brake is feasible to be used in motorcycles. The result from the simulation shows that the braking torque produced is sufficient to instantly stop the motorcycle with less deceleration effect on the driver. Numerous studies extended the MRF braking system concept to develop a clutch system (Bucchi *et al.*, 2013; Wang *et al.*, 2015b; Wang *et al.*, 2013a; Wang *et al.*, 2013b). These studies focused on designing an optimal transmission system with high torque coupled with the use of minimal current. Both the brake and clutch showed that the MRF is an emerging technology to be applied in the future. A polishing method also showed a significant advancement for developing mechanical components using MRF technology.

In order to understand the effect of particle size on the rheological properties of MRF polishing fluid, Jha and Jain (2009) developed a special magneto-viscometer. Three viscosity constitutive models were fitted from experimental data. These models were the Bingham plastic, Herschel-Bulkley, and Casson Models. Pan and Yan (2015) focused on experimental work of understanding the material removal mechanism in MRF polishing. An experimental study conducted by Niranjan and Jha (2015) contributed significantly toward understanding the effect of the MRF polishing process on the tool life. The flow behaviour of MRF polishing directly affected the final product. This flow behaviour was studied by Das *et al.* (2015) where the analytical and numerical models were explored in modelling the fluid flow. This fundamental work showed that the study of MRF properties in the polishing process is still in progress. Many other researchers worked on developing the MRF polishing system. Shi *et al.* (2012) combined the MRF polishing head into a numerical machine to determine the advantages of controllability and accuracy of the system. A combination of MRF polishing with chemical machining was explored by Jain *et al.* (2012). The system successfully enhanced the surface finish for micro-machining products. Concave geometry is a challenge in the MRF polishing system while the fluid tends to flow to other areas leading to difficulty in controlling the performance of the polishing process. A novel method to solve concave surface polishing was introduced and improved by Chen *et al.* (2015b). Another example of successful application of MRF polishing is in improving a piece cavity in a wired electric discharge machining (Wang *et al.,* 2015c). Clearly, the MRF polishing research has many areas of application.

Besides conventional mechanical devices such as damper and brake, MRF also shows significant advantages in many other applications. Kaluvan *et al.* (2014) and Kaluvan and Choi (2014) manipulated shear and squeeze modes of MRF to design a novel sensor for current and resonance of wave detection. In an application where space is a major constraint, the multifunctional actuator requires careful design. To answer this, Guo and Liao (2012) designed a rotary multifunctional actuator using the MRF. The finite element analysis revealed that the multifunctional actuator could possibly provide the desired force. In more advanced applications, Kaluvan *et al.* (2015) developed a microactuator system using MRF. Their experimental result suggests that the micro motor in the MRF could be implemented in real industrial applications with minimal modification in design. The most challenging application of MRF is in developing a valve for controlling the hydraulic system.

2.3.2 MRF Valve

The MRF-based control valve provides flow control by varying the electrical current to an electromagnet that affects the apparent viscosity of the MRF (Wu *et al.,* 2011). Increased electric current provides an increased magnetic field, which in turn, increases the apparent viscosity of the fluid. This means that the flow rate through the valve can be controlled. Figure 2.7 illustrates the fluid flow through the valve.

MRF valve is a device commonly used to control the speed of the MRF or hydraulic actuator. The performance of valve depends on the magnetic circuit design. The MRF valve is a key component of the MRF actuation system (Salloom & Samad 2011). Using MRF valves in MRF actuation systems have many advantages, including: (1) valves have no moving parts, and (2) electronic flow control via an electromagnet. The most important advantages of an MRF valve will be weight savings and reduction in complexity and no-moving parts as compared to a mechanical valve.

MRF valve has the potential to improve the performance of the hydraulic system, especially in terms of accuracy and reduced complexity in fabrication. Many researchers are working on designing and optimising the performance of the valve (Nguyen *et al.*, 2007; Nguyen *et al.*, 2008; Wang *et al.*, 2009) by optimising control energy applied to the valve while considering parameters such as current, geometrical dimension, and coil wire size. Similarly, the optimisation of the orifice in the valve has been explored (Grunwald & Olabi., 2008; Li *et al.*, 2014). Nguyen *et al.* (2009) worked on the design of the optimal dimension and valve structure using an analytical solution.

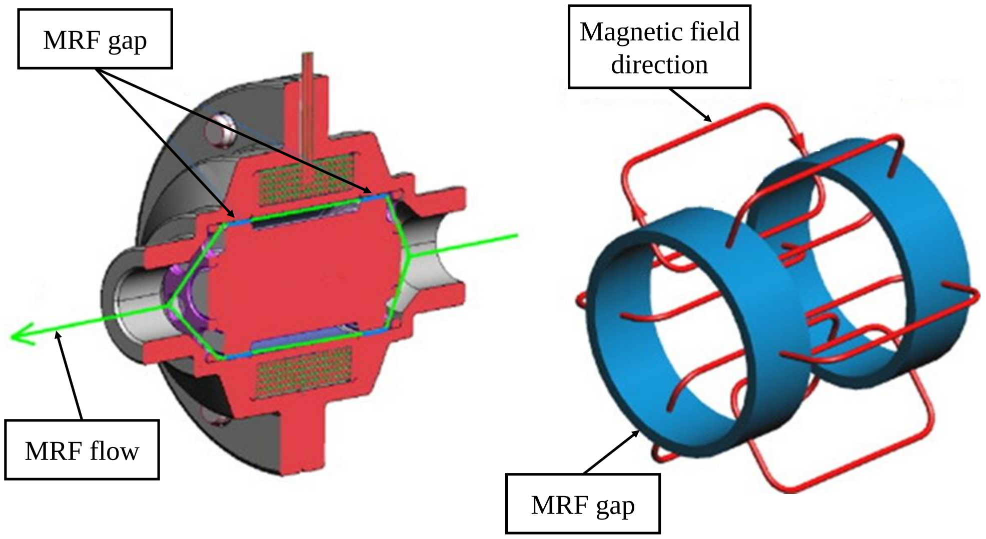


Figure 2.7 MRF single valve (Grunwald & Olabi, 2008)

The analytical model has been further used to determine a maximum yield stress and pressure drop by varying the geometry. In order to achieve a size reduction in the valve, Ichwan (2014) successfully demonstrated a novel design for an MRF valve, using the meandering flow path. This type of design can minimise the size of the valve while maintaining sufficient pressure to operate the valve.

An optimal valve design is useful for designing the MRF damper (Moon *et al.*, 2011). The MRF damper is controlled by the orifice opening acting as a valve. The damper performance can be increased by optimising the valve geometry. Optimising the orifice flow in the damper was studied by other researchers (Fujitani *et al.*, 2002; Høgsberg & Krenk, 2008; Milecki, 2001). Work on MRF valve design also can be seen in the energy absorber system where Hu *et al.* (2007) designed the bypass valve to create an absorbing mechanism. Coil dimensioning directly affects the core induction in MRF. Thus, studying the coil diameter and structure are compulsory in developing an optimal valve design. Daniel *et al.* (2015) developed an analytical model for the valve to search for the best combination of coil structure and valve core.

Nishiyama *et al.* (2011) showed that the MRF valve design offers significant improvement in the bio-medical application. As shown in his experimental work, it is important to consider the valve wall effect on the fluid flow behaviour for micro-scale applications such as in medical devices. The MRF valves produced to date have yet to replace the conventional 4/3 proportional directional hydraulic valve because of its shape and extension of the complex system. The role of the 4/3 proportional directional valve in the hydraulic system is very important because it can effectively control the movement of the double acting cylinder. To solve this problem, Salloom and Samad (2011) successfully designed MRF valves that are compact and suitable for controlling of a double-acting hydraulic cylinder. The MRF system with the invention of the valve