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

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by

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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 ($\mathrm{cm}^3/\mathrm{sec}$)
$\dot{\gamma}_0$	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