UNIVERSITI TEKNIKAL MALAYSIA MELAKA

SLIDING MODE CONTROL (SMC) IN FRICTION COMPENSATION

This report submitted in accordance with requirement of the Universiti Teknikal Malaysia Melaka (UTeM) for the Bachelor Degree of Manufacturing Engineering (Robotic & Automation)

by

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BORANG PENGESAHAN STATUS LAPORAN PROJEK SARJANA MUDA

TAJUK: **SLIDING MODE CONTROL (SMC) IN FRICTION COMPENSATION**

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I hereby, declared this report entitled "Sliding Mode Control in Friction Compensation" is the results of my own research except as cited in references.

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APPROVAL

This report is submitted to the Faculty of Manufacturing Engineering of UTeM as a partial fulfillment of the requirements for the degree of Bachelor of Manufacturing Engineering (Robotic and Automation). The member of the supervisory committee is as follow:

………………………………………

ABSTRAK

Prosess mesinan telah mengalami berkembangan yang mendadak dari masa ke masa untuk menyesuaikan diri terhadap peningkatan permintaan dalam kelajuan, ketepatan dan kecekapan. Perubanhan mahupun peningkatan paradigma ini telah menghasilkan satu cabaran yang baru malah kritikal. Projek ini bertujuan untuk menangani beberapa isu seperti yang dinyatakan, iaitu penyelarasan terhadap kesan geseran pada ketepatan prosess mesinan.

Masalah tentang kesan geseran dalam prosess mesinan telahpun dikaji dengan banyaknya di masa dulu dan pelbagai teknik mahupun idea telah dicadangkan dan dikesahkan. Teknik kawalan linier yang sederhana seperti PI, PID atau kawalan riam bersendirian adalah tidak mencukupi untuk menyelaraskan perilaku geseran yang tidak linier. Dengan ini, suatu teknik kawalan yang kuat iaitu “sliding mode controller (SMC)” telah dicadangkan sebagai teknik kawalan dalam projek ini, dalam menyelaraskan geseran semasa gerakan pembalikan suatu sistem drive untuk meningkatkan ketepatan sistem itu. Prestasi kawalan dalam penyelarasan dinilai berdasarkan kebesaran “quadrant glitches”, iaitu satu produk daripada perilaku kompleks yang sangat tidak linier atas titik dimana pergerakan pembalikan motor berlaku dan ia ditandakan atas kehadiran “paku” di dalam setiap sukuan bulatan. Akhir sekali, kebolehan alat kawalan SMC dalam geseran penyelarasan dibandingkan dengan kebolehan alat kawalan PID.

ABSTRACT

Machining processes have evolved significantly over time in order to adapt to the increasing demand for speed, accuracy, and efficiency. This evolution or paradigm shift has created new and highly critical challenges. This project aims at addressing some of these issues, namely the compensation of the effect of friction forces on the accuracy of the machining process.

Issues regarding friction effects in machining process have been studied extensively in the past and various techniques and ideas have been proposed and validated. Simple linear feedback control techniques such as PI, PID, or cascade control alone are insufficient to compensate the nonlinear friction behavior. Hereby, a robust controller, namely sliding mode controller (SMC) is proposed as control technique in this project in compensating friction force during motion reversal of a drive system in order to increase the system's accuracy. The controller's compensation performance is measured based on the magnitude of quadrant glitches, a product of highly non-linear complex behavior at the point of motor reversal motion and it is characterized by the presence of "spike" in each quadrant of circle. Lastly, the controller's performance is compared with the performance of PID controller in compensating friction forces.

DEDICATION

This report is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

ACKNOWLEDGEMENT

This report would not have been possible without the guidance and the help of several individuals who in one way or another contributed and extended their valuable assistance in the preparation and completion of this project.

First and foremost, my utmost gratitude to my respected project suprvisor as well as panel, Dr. Zamberi Bin Jamaludin, for his support, useful guidance, encouragement, valuable advice and constructive comments during the time this final year project was being developed. Besides, thousand thanks to my project examiner, Mr. Mohd Nazrin Muhammad, thank you for the guidance and supportive.

Afterward, I would like to thank UTeM lecturers and tutors who give theirs guidance and advices to me in conducting my project successfully. Other than that, special thanks to Ms. Suhani Shara, who provides useful guidance and information in assisting me in completing my project.

Moreover, thank you to my friends, Mr. Chiew and Mr. Leo. I really appreciate for their helping hands in sharing useful information with me in conducting my project.

Lastly, I offer my regards and blessings to all of those who supported me in any respect during the completion of the project.

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SMC	-	Sliding Mode Control
GMS	-	Generalized Maxwell-slip
PI	-	Proportional –plus-integral Controller
PID	-	Proportional-plus-integral-plus-derivative Controller
FRF	-	Frequency Response Function
RC	-	Repetitive Control
VSC	-	Variable Structure Control
FYP	-	Final Year Project

CHAPTER 1

INTRODUCTION

1.1 Project's title: Sliding Mode Control (SMC) in Friction Compensation

1.2 Background

Nowadays, control systems contribute significantly in almost every aspect of our modern society with widespread applications in home environment and the industry. In industry, there is significant demand for high speed and high accuracy machine tools. These demands will translate to good performance. In a drive's system, one factor that contributes its performance is the influence of friction forces. Friction is an undesired nonlinear phenomenon that reduces the positioning and tracking accuracy in mechanical systems. An occurrence that is caused by friction is known as "spike" that is visible at quadrant locations during circular motion. These spikes are generally known as quadrant glitches, which is the product of complex nonlinear behavior of friction at motion reversal or near zero velocity on each axis of a motion system. This project focuses on the development of control technique to compensate friction force during motion reversal of a drive system in order to increase the system's accuracy.

1.3 Problem Statement

Friction is an undesired nonlinear phenomenon, which reduces positioning and tracking accuracy in a drive system. By studying the behavior of friction and the friction models, friction forces can be compensated. Several methods exist in literature for friction compensation. A nonlinear controller in this project, Sliding Mode Control (SMC) is applied and designed as compensator necessary to improve tracking performance of a drive system.

1.4 Objective

There are several objectives outlined for the project. The objectives are:

i. Study the behavior of friction
ii. Study the friction models and
iii. Develop a control technique (SMC) to compensate friction

1.5 Scope

The scopes of this project are:

i. Study and apply the Generalized Maxwell-Slip (GMS) friction model based on actual friction's behavior extended from previous work of Jamaludin (2008).
ii. Design of sliding mode controller for friction compensation using MATLAB/Simulink.

1.6 Outline

This research and project report consists of several chapters. The following *Chapter 2* introduces literature review on friction behavior, several friction models and techniques of compensation. The minimization of the effect of friction forces on the system position and tracking performance requires precise knowledge and complete understanding of the characteristics of this disturbance forces. *Chapter 3* discuss the overall flow of conducting this research project from the beginning of the studying of Generalized Maxwell-Slip (GMS) friction model until the design of sliding mode control (SMC) for friction compensation. *Chapter 4* discuss on the result based on the flow presented in previous chapter and the performance of compensation on friction forces on tracking performance is analyzed. *Chapter 5* discuss on the discussion based on the result obtained and lastly *Chapter 6* discuss on the conclusion of this research project and the further work of this project.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In high precision positioning applications, the effects of friction present in the system can lead to significant positioning error. An unambiguous phenomenon which is caused by friction is known as “spike” at quadrant position during circular motion or most commonly known as quadrant glitches (refer to figure 2.1). These quadrant glitches are the product of complex nonlinear behavior at motion reversal of a motion system that can critically affected the tracking performance (Jamaludin, 2008). In order to compensate the error due to frictional forces, an effective control strategy is a prerequisite. This requires a deep understanding and knowledge regarding on the friction behavior and friction characteristic as well. This chapter covered on the understanding, characterization and modeling of friction behavior. Generalized Maxwell-Slip model (GMS) is adapted to sliding mode control (SMC) in this project and will be further validate through simulation. The parameters of GMS model is obviously not be enclosed in this chapter but will be covered in the coming result chapter.

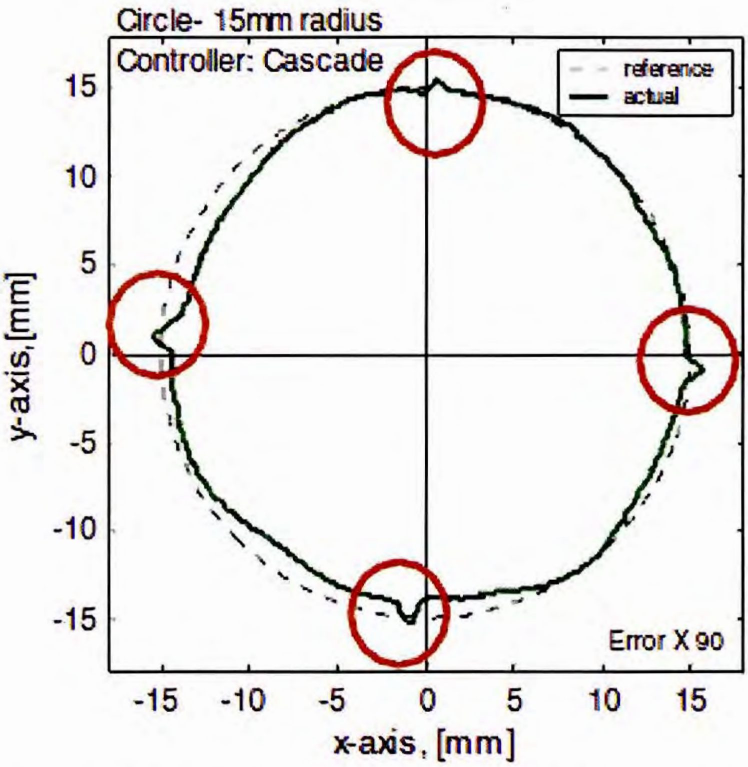

Figure 2.1: Quadrant glitches from a circular test (Figure reproduced from Jamaludin *et al.*, 2008)

This project considers the widely known Generalized Maxwell-Slip model for friction compensation due to its accuracy. The static friction model is conferred in the following section and the basic structures of Dahl, LuGre, Bristle and Generalized Maxwell-Slip friction models are summarized as follow.

2.2 Friction Models

2.2.1 Static Friction Model

Static friction is the friction when sticking. The force required to overcome the static friction and initiate motion is called the break-away force. The main idea is that friction opposes motion and that its magnitude is independent of velocity and contact area. The friction-velocity relationship is illustrated as in figure 2.2.

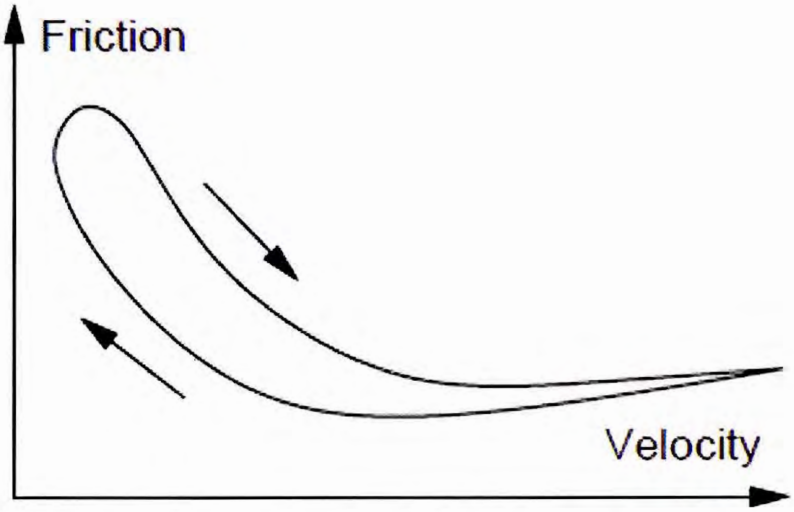

Figure 2.2: The friction–velocity relationship. The friction force is lower for decreasing velocities than for increasing velocities. The hysteresis loop becomes wider as the velocity variations become faster (Figure reproduced from Olsson *et al.*, 1997).

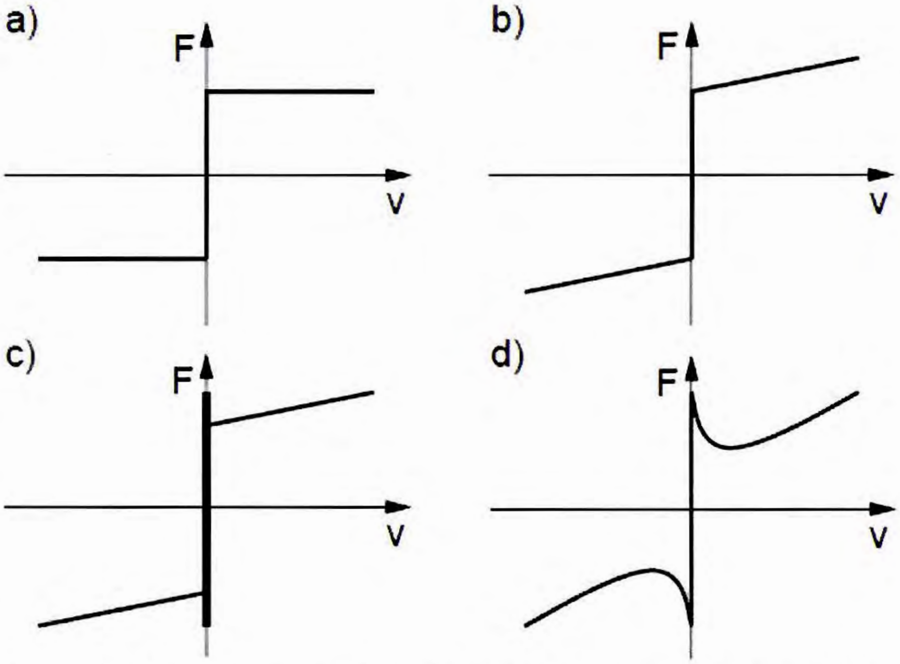

Figure 2.3: Different friction component in static friction models. Figure a) shows Coulomb friction and figure b) Coulomb plus viscous friction. Stiction plus Coulomb and viscous friction is shown in figure c) and figure d) shows how the friction force may decrease continuously from the static friction level (Figure reproduced from Olsson *et al.*, 1997).

There are different friction component in static friction models (refer figure 2.3). Static friction models describe the steady-state friction behavior in sliding regime only and hence are dependent on the sliding velocity v. The considered static friction only and hence are dependent on the sliding velocity v. The considered static friction model incorporates Coulomb, viscous, and Stribeck friction as described in equation (2.1).

$$F(v) = \left\{F_C + (F_S - F_C) \cdot exp\left[-\left|\frac{v}{V_S}\right|^{\delta}\right] + \sigma \cdot |v|\right\} \cdot sign(v). \quad (2.1)$$

Where F_C, F_S and σ represent the Coulomb, static, and viscous friction coefficients respectively. The Stribeck effect represents a decreasing effect of friction forces with increasing velocity. The Stribeck friction model parameters are the Stribeck velocity V_s and the Stribeck shape factor δ.

The Dahl model is covered in the following session.

2.2.2 The Dahl Model

The development of the Dahl model is purposely for simulating control systems with friction. This model has been used for adaptive friction compensation. Dahl's starting point was several experiments on friction in servo systems with ball bearings which indicate that there are metal contacts between the surfaces. One of his findings was that bearing friction behaved very similar to solid friction. Dahl is then developed a comparatively simple model that was used extensively to simulate systems with ball bearing friction (Olsson *et al.* 1997). The model is an extension to the classic Coulomb friction, with smooth transitions around the critical zero velocity regions. A generalized first order differential equation of the position that is a function of the sign of the velocity v, approximates the hysteresis at pre-sliding regime as shown in equation (2.2) below (Jamaludin, 2008).

$$\frac{dF_f}{dx} = \sigma_0 \left|1 - \frac{F_f}{F_s} sgn(v)\right|^{\delta_d} sgn\left(1 - \frac{F_f}{F_s} sgn(v)\right). \quad (2.2)$$

Where F_f and F_s are the total friction force and the static friction force respectively with σ_0 is the initial stiffness of the contact at velocity reversal, and δ_d determines the shape of the hysteresis.

The LuGre friction model, which is the improvement as well as the extension from the Dahl model that combines the pre-sliding friction behavior of the Dahl model with the steady-state friction characteristic of the sliding regime, will be covered in the following section.

2.2.3 The LuGre Model

The LuGre model is a dynamic friction model and friction is modeled as the average deflection force of elastic springs. When a tangential force is applied the bristles will deflect like springs. If the deflection is sufficiently large the bristles start to slip. The average bristle deflection for a steady state motion is determined by the velocity. It is lower at low velocities, which implies that the steady state deflection decreases with increasing velocity. This models the phenomenon that the surfaces are pushed apart by the lubricant, and models the Stribeck effect (Olsson *et al.*, 1997).

The model is based on the concept of averaging deformation of the contact asperities. The friction force is defined as:

$$F_f = \sigma_0 z + \sigma_1 \frac{dz}{dt} + \sigma_2 v. \tag{2.3}$$

σ_0 , σ_1 , and σ_2 are the asperity stiffness, micro-viscous friction coefficient, and viscous friction coefficient respectively. The state variable z represents the average deflection of the asperities and v is the velocity.

$$\frac{dz}{dt} = v - \sigma_0 \frac{v}{s(v)} z. \tag{2.4}$$

$s(v)$ is the Stribeck curve, that is, a decreasing function for increasing velocity with upper limit and lower limit bounds corresponding to the static friction force $F_s$and Coulomb friction force F_c respectively (see section 2.1.1). V_s is the Stribeck velocity and δ is the Stribeck shape factor.

$$s(v) = sgn(v)\left[F_c + (F_s - F_c)e^{-\left|\frac{v}{V_s}\right|^{\delta}}\right]. \tag{2.5}$$

However, the LuGre model fails to describe the hysteresis nonlocal memory behavior of friction force in pre-sliding regime which is then bring to the development of the generalized Maxwell-slip (GMS) model, proposed by Al Bender *et al.* (2005) which addressed this limitation.

The Generalized Maxwell-slip (GMS) friction model will be discussed in the next section.

2.2.4 The Generalized Maxwell-Slip Model (GMS)

Lampaert *et al.* (2003) proposed the GMS friction model that incorporates the components of: the Stribeck curve for constant velocity, the hysteresis function with non-local memory for the pre-sliding regime, and the frictional memory for the sliding regime. The structure of this model is similar to the Maxwell-slip structure, that is, it consists of a parallel connection of N different elementary slip-blocks and springs (see figure 2.4). Each block represents a generalized asperity of the contact surface that can either stick or slip and each element i has a common input z, an elementary stiffness k_i, a state variable α_i that describes the element position, a maximum elementary Coulomb force W_i and a friction output F_i. A new state equation that characterizes sliding dynamics of each elementary slip-block replaces