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Study on effect of sigmoid like curves in pre-sliding regime on ball screw driven positioning stage

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***Abstract*— Frictional behaviour becomes main study in machining, especially for ball screw driven positioning stage. This paper presents friction behaviour analysis in pre-sliding regime using various mathematical models that produce a sigmoid like curve. In pre-sliding regime, friction behaviour is described while axes moving at relatively low velocity. Furthermore, a smooth continuous curve is needed in the transition between sliding regimes. Generalized Maxwell Slip (GMS) model is known model that well describes the friction behaviour at pre-sliding regime. Sigmoid like function is proposed as a significant parameter in modified GMS. The numerical simulation was performed to show the influences and effects for each sigmoid like curve. The result analysis leads to the development of an adaptive friction compensation model.**

***Keywords*—pre-sliding regime, sigmoid, ball screw, friction compensation model**

I. Introduction

Positioning and tracking accuracy is often an issue in producing high productivity and quality of machine tools. The ball screw drives are mostly used because of great capabilities in velocity and acceleration, high efficiency and simple pre-stressing [1]. Because of that reason, it is dominantly chosen in machine construction market. However, ball screw driven stages with its properties and handling, produces non-linear friction to be compensated [2]. There are several assessments that have designed to evaluate the friction caused by a ball screw driven stage. Stick-slip motion can provide parameters of non-linear friction. [3]. Non-linear friction covers sliding and pre-sliding friction.

Until recent years, many researches focus on reducing errors and design robust controller accordingly in pre-sliding friction. Pre-sliding regime is where displacement is a function of motion. Within the time interval for velocity reversal, there is a sudden change of torque. Normally this situation leads to system chattering due to the discontinuity. A sigmoid function is been introduced to overcome the issue where it is expected to make ideal continuous motion between sliding regime. [4]

Sigmoid function widely used as basis of neural network and sliding mode control [5][6][7]

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In sliding mode control, a sigmoid function is implemented to reduce chattering in system. Tjahjowidodo [8] suggest sigmoid function in compensation model to control discontinuity around zero position error. In a study of significant parameter in modeled a sigmoid function, Park stated that α, is the slope of the sigmoid function, with supported by scaling factor and a bias for adjusting the magnitude of the function.[4]

Another study of the sigmoid function in modeling showed that a suitable number of sigmoid functions are important. Shang et al. [9] found that the higher number of the sigmoid function improved accuracy but more complicated. A broader perspective has been adopted by Piatkowski who introduced sigmoid like curve to compensate pre-sliding friction. A sigmoid like curve has the shape as the letter S [5].

This paper describes the study of the effectiveness of sigmoid like curve for a ball screw driven positioning stage. This paper is organized as follows. Section II provides an overview of frictional behavior including sliding and pre-sliding regime in a continuous motion. Section III describes an analysis of simulation results. Several function equations, $f_j(x)$ where $(j=1,2\ldots)$ based on previous research done which draws a sigmoid like curve. Section IV concludes the finding and gives recommendation for future works.

II. Frictional behaviour of ball screw driven positioning stage

Frictional behavior is identified to be in the form of sliding-pre-sliding-sliding regime. Much research has been done to compensate friction especially on ball screw driven positioning. It has been studied that nonlinear frictions caused by a ball screw driven are Stribeck effect and rolling friction [2]. Whereas static friction affects the circular contour accuracy at near zero velocity and begins to move[10].

A survey that has been carried out by Armstrong et al [11] and highlights onto two important behaviours:

- Elastically deformed and rise in pre-sliding regime
- Plastically deformed and rise to static friction

Pre-sliding regime is where breakaway point occurred. Pre-sliding displacement is a breakaway displacement. Xi [10] stated that the static friction is at maximum value when breakaway displacement has been reached. Static friction drop to zero when breakaway displacement is in the end.

Al-Bender and Lampaert [12] defines that pre-sliding is where friction force dominantly a hysteresis non-local memory of the displacement. In many years, research is continuously done on compensating friction based on pre-sliding regime. Dahl, Lugre, Leuven model and Generalized Maxwell Slip (GMS) are compensation model based on pre-sliding regime and hysteresis with nonlocal memory [11][13][14][15].

Dahl and Lugre model have been well described by Lampaert et al. [16]. The study showed that Dahl model provides a smooth transition near zero velocity. The frictional hysteresis is located at pre-sliding regime. Another finding is the model is approximated by first order differential equation of position. Lugre model integrates pre-sliding behavior of Dahl with steady state friction characteristics in sliding regime. The study has been continued with efficacy of Leuven and GMS model. Leuven model is an improvised Lugre model to get better tracking results at velocity reversal.

GMS model is defined basis of three friction properties which are (1) Stribeck curve at constant velocity. (2) Hysteresis function with nonlocal memory at pre-sliding. (3) Frictional memory in sliding regime [16]. The effectiveness of GMS model in friction compensation is still been investigated until recent years. Numerous studies have attempted to demonstrate improvised GMS model [5] [17] [18]. In another study of GMS model, Bona [19] found that the friction compensation has to be supported with an observer for friction internal state estimation if dynamic friction affects pre-sliding phase.

III. Simulation result

A. *Sigmoid curve*

Sigmoid function is placed at pre-sliding regime. Switching line between both sliding regimes is smoothly connected with a sigmoid function. Figure 1 shows sigmoid curve function at pre-sliding regime.

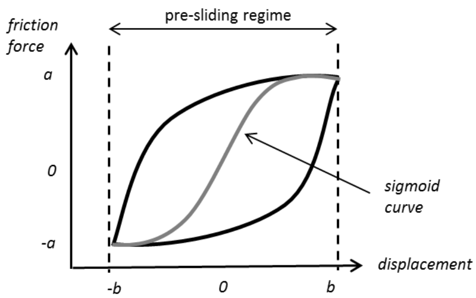


Figure 1 Sigmoid curve at pre-sliding regime

In pre-sliding regime, friction behaves as a hysteresis function of displacement with non-local memory behaviour. It is dependent to the displacement. Similar to step for identifying Generalized Maxwell Slip model, displacement of a sinusoidal excitation of the system is evaluated for approximation of the sigmoid function. Figure 2 demonstrates the ideal sigmoid curve that smoothly connected between sliding regime for better friction compensation.

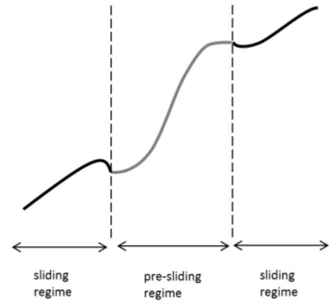


Figure 2 Sigmoid curve for smooth link in between sliding regime

This paper discusses possible equations that give sigmoid like curve for a ball screw driven XY milling table. The system is powered by Panasonic MSMD 022G1U AC servomotor. It is equipped with incremental encoder with resolution 0f 0.0005 millimeter/pulse respectively.

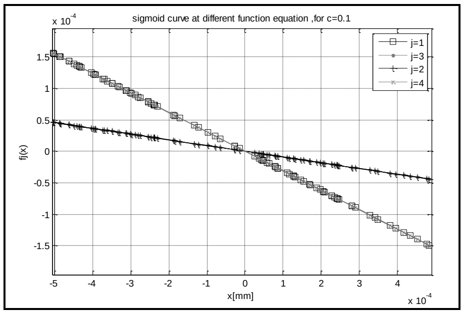
B. *Result Analysis*

Piatkowski in recent research has introduced M-GMS model based on several mathematical equations that produce sigmoid like curve. Ideally, sigmoid curve is designed to give smooth link between sliding regime as well as to compensate friction behavior. Table 1 shows an example of the equation applied to simulate a sigmoid curve response for ball screw driven positioning stage. $f_1(x)$ and $f_3(x)$ are claimed to be preferred for GMS approximation. [11]

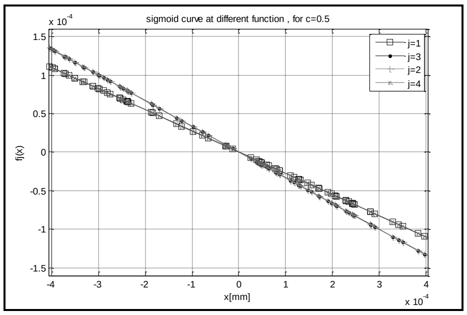
TABLE 1 EQUATION APPLIED FOR SIMULATION

j	$f_j(x)$
1	$-\text{atan}(x)/(\pi + C)$
2	$-Cx/((1+x^2)^C + C)$
3	$-Cx/((1+\lvert x\rvert) + C)$
4	$-\text{atan}(\sinh(x))/(\pi + C)$

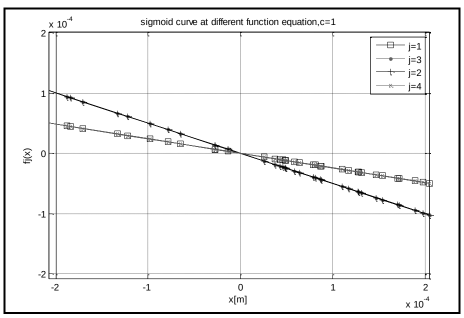
C in the equation is a constant that gives effect on sigmoid curves. A simulation using C = 0.1, 0.5 and 1 is tabulated in Figure 3(a),(b) and (c).



(a)



(b)

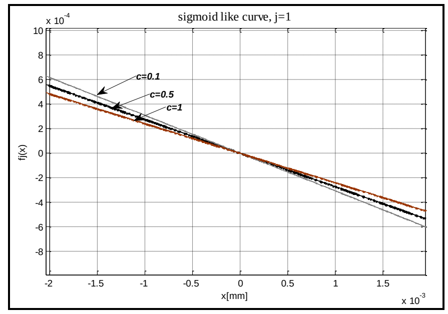


(c)

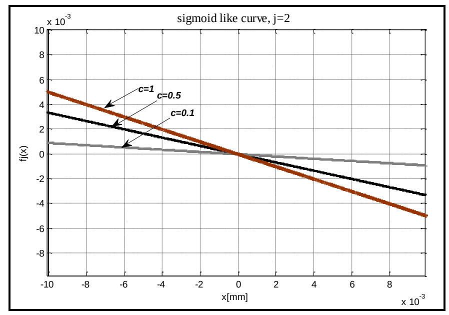
Figure 3 shows sigmoid curve at different function equation with (a) c=0. 1 (b) c=0. 5 (c) c=1

As shown in Figure 3, form of the graph is similar between sigmoid curve with constant, C= 0.1 and C=1. Apparently in these graphs, $f_1(x)$ and $f_4(x)$ are plotted at same linear line. While, $f_2(x)$ and $f_3(x)$ is at the other linear line. Most is preferable to the sigmoid curve with constant, C=0.5 where its difference is not significant within different function equations.

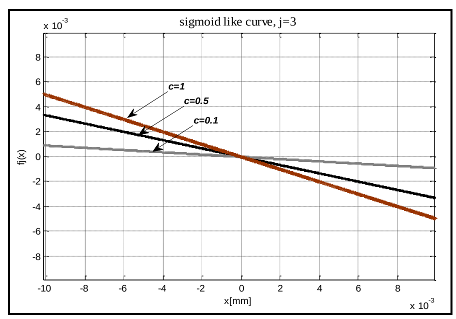
Figure 4(a), (b), (c) and (d) compares the results obtained by different constant, C for each function equations, $f_j(x)$ ($j=1,2,3,4$).



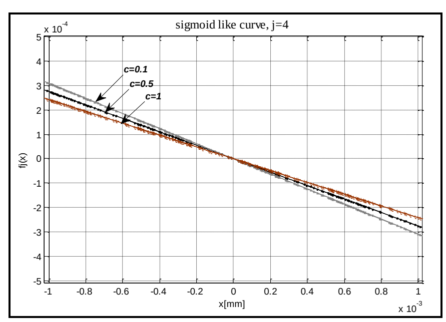
(a)



(b)



(c)



(d)

Figure 4 shows sigmoid curve at different C with (a) j=1, (b) j=2, (c) j=3, (d) j=4

It can be seen from the graph that function equation $f_1(x)$ and $f_4(x)$ not give significant difference with different constant, *C*. However, $f_2(x)$ and $f_3(x)$ provide trends in response by increasing gradient of the slope when constant, *C* is decreasing.

IV. Conclusion

This paper has evaluated and presented the effectiveness of different function equations with different constant, *C* to produce sigmoid like curve. The assessment is done by using a ball screw driven XY milling machine. As a result, it shows that lower constant, C provides higher gradient of the slope. In term of function equation, $f_1(x)=-atan(x)/(\pi+C)$ and $f_4(x)=-atan(sinh(x))/(\pi+C)$ have slightly difference with constant, *C* varies. Another finding was that constant, *C*=0.5 shows consistency in small difference with varies function, $fj(x),(j=1,2,3,4)$. Further research may explore the efficacy of sigmoid like curve function to be the basis of adaptive implementation.

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