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MODELING AND EXPERIMENTAL IDENTIFICATION OF FRICTION NONLINEARITY IN A BALL SCREW MECHANICAL TRANSMISSION TYPE IN A GANTRY ROBOT

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Abstract. *This work objective present the methodology for the experimental identification of friction characteristics, and develop and experimentally validate the mathematical model of a joint in a Gantry robot with transmission by ball screw and electric drive gearbox for alternating current and inverter frequency. The dynamic modeling of mechanical mechanisms can provide important information for design aspects and robot construction and the subsequent development of control strategies. However the mechanical systems are affected by nonlinearities as friction. The friction displays nonlinear characteristics that are not always considered in the modeling and development of controllers, which causes errors in the development and validation of mathematical models and consequently difficulties in accurate control of robots. For the identification and experimental validation, was used a prototype of a prismatic joint of a Gantry robot. The main contributions of this paper are the proposal of a methodology for the experimental identification of nonlinear of friction characteristics and the static friction map which shows where the predominant features in the prototype of a robotic joint type ball screw, and the model validation mathematical considering friction. The research is part of a university interaction design with the participation of high school teachers and students.*

Keywords: *mathematical modeling, friction nonlinearity, Gantry robot, experimental identification*

1. INTRODUCTION

The use of Gantry robots type in your applications (such as winch robot and CNC machining, for example) grew and have become more complex and consequently more expensive (PO-NAGEN, 2009, p. 1588). The Gantry robots have perpendicular prismatic joints and are safe, adaptable, with good relation between quality and productivity (Shang and Cong, 2014) to the detriment of other types of robots. The use of ball screw transmissions is widely used for presenting stability, efficiency, accuracy, durability and cost advantages (Shimada *et al.*, 2013).

The research is part of a university interaction design with the Community and has the participation of high school teachers and students, engineering and graduate school students, where study performance characteristics of the proposed technological solutions, thus encouraging the study science and technology, contributing to improved training in the field of automation and discovering talents from the proposed challenges. The development of research project is supported by CAPES/FAPERGS (process number 01628-2551/14-6, edictal number 3/2014: Program in Science Initiation, Mathematics, Engineering, Creative Arts and Technologies - PICMEL) and also aims to arouse the interest of students for the creation and innovation of engineering solutions. The experimental prototype was developed and tested in UNIJUÍ Câmpus Panambi University.

However, the use is strictly related to precise control aspects which are affected by nonlinear characteristics such as friction. Friction can be responsible by problems such as the generation of errors/limit cycles following trajectories causing stick-slip effects (alternating movements and refreshments), oscillations (*hunting* - the movement ranges around a given position constant), loss of motion (*standstill* - occurs when the system is held at refreshments in a time where speed is zero), failure quadrature (*quadrature glitch* - following the deviations of a multi-axis movement), among other difficulties for control and stability (Canudas de Wit et al., 1995). For show several classic features such as static friction, Coulomb, viscous, drag and more complex as the friction Stribeck, increasing static, friction memory among others (Sanca, 2006), which affect the dynamic behavior of the system as a whole and consequently the development of control strategies.

These friction characteristics are difficult to identify since they depend on some aspects such as speed, temperature and direction of movement. Thus, present in this paper the identification of the friction characteristics through the static friction map of a robotic joint Gantry type, with the later inclusion and validation of the features in the dynamic model of the robotic joint. Therefore, this paper is organized into four sections. At first it is the dynamic modeling of friction and robotic joint. The second shows the methodology for identification of friction characteristics and its inclusion in the present dynamic model. At the end of the dynamic model with the dynamic friction is validated and presents the conclusions and future prospects.

2. DYNAMIC MODELING

The nonlinear characteristic of friction is present in all mechanical mechanisms that incorporate movements. Study it and understand it is important to understand the effects of such mechanisms, in order to compensate and consequently reduce its effects.

There are many friction characteristics. The static friction (F_s) occurs when the speed is zero and has opposite direction of the movement with magnitude of force (or torque) applied to a maximum value of static friction force. The Coulomb friction (F_c), also known as dry friction, and is independent of the contact area, being opposite to the motion relative and proportional to normal force of contact. The viscous friction (F_v) corresponds to a situation of good lubrication and is linearly proportional to speed. The frictional drag (F_a) refers to the friction caused by resistance to movement of a body, and is proportional to the square of the speed (resulting in many cases of a turbulent flow).The Stribeck friction ($\dot{y}_s$) is a nonlinear friction phenomenon that occurs at low speeds of the friction curve where the slope is negative.

The combination of the friction characteristics mentioned so far, result in a not linear function like that shown in Fig. 1which are related to force of friction (F_{atr}) and the speed at steady state ($\dot{y}(t)$).

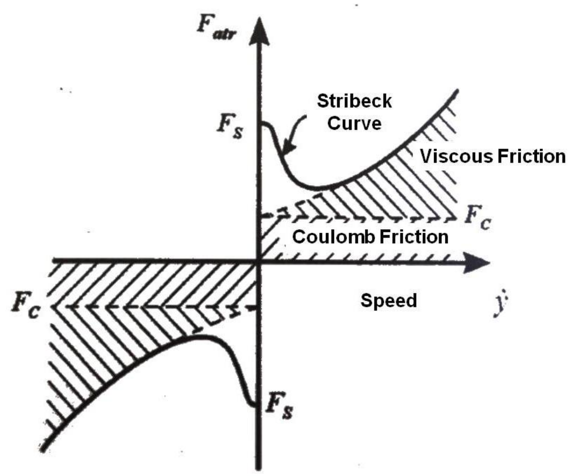

Figure 1. Combination of Friction Characteristics in Steady
Source:Valdiero 2012.

Although there are other characteristics of the nonlinear friction, these and combinations thereof mentioned above are very important in understanding the dynamics as a whole.

The dynamic model called LuGre (Canudas de Wit *et al.*, 1995) besides includes the features described, is based also on the micro deformations that occur between the contact surfaces. When a tangential force is applied, the elastic bristles will deflect as springs. If these deflections are large enough, the bristles will slide (*stick-slip*). The speed is what determines the average deflection of the bristles in the movements on a steady state, which is modeled by Stribeck friction (Sanca, 2006). The dynamic friction is given by Eq. 1.

$$F_{atr} = \sigma_0 z + \sigma_1 \dot{z} + \sigma_2 \dot{y} \quad (1)$$

where F_{atr} is the strength of the friction dynamic on the LuGre model. The dynamic parameters σ_0 and σ_1 are the rigidity coefficient of the microscopic deformations between the surfaces in contact during “pre slip” regime and the damping coefficient associated with the variation rate z (so $\dot{z}$), respectively. The static parameter σ_2 is the viscous damping coefficient (commonly referred to as B). The dynamic of internal state of the friction is called for z, which describes the average deflection of the surfaces in contact during the phase of static friction or in other words, deformation of the "pre slip" movement. Finally, the parameter $\dot{y}$ represents the relative speed between the surfaces. The Eq. 1 can be rewritten using Eq. 2 describes the static friction map contemplating the characteristics described

$$F_{atr} = \left(F_c + (F_s - F_c)e^{-\left(\frac{\dot{y}}{\dot{y}_S}\right)^2} \right) sgn(\dot{y}) + \sigma_2 \dot{y} \tag{2}$$

where F_c is the Coulomb friction and F_s is the force of static friction and $\dot{y}_s$ is Stribeck speed.

This model can be incorporated into the dynamic model of prismatic joint whit ball screw transmission, which is described by Eq. 3, which was obtained by the Newton-Euler method from the dynamic balance in the free body diagram (Sciavicco and SICILIANO , 1996).

$$M_{eq}\ddot{y} + F_{atr_{eq}} = \frac{2\pi}{p} T_m \tag{3}$$

The Eq.3 indicate that the mass moved about the screw axis (M_{eq}) depends on the acceleration ($\ddot{y}$) added to the friction force ($F_{atr_{eq}}$ described in Eq. 2) results in a reaction force that depend on the step (p) and the motor torque applied (T_m). The model shown in Eq. 3 only refers to the mechanical part, given that despite the robot having electric drive, this dynamics was considered much faster than the mechanical dynamics.

3. EXPERIMENTAL IDENTIFICATION OF FRICTION AND STATIC MAP

To identify the nonlinearity of friction, was built an experimental stand of a joint Gantry robot with transmission by ball screw and gear motor driven by alternating current and frequency inverter. This stand is connected to a dSPACE 1104 responsible for making acquisition of signs of linear and angular displacement sensors installed on Gantry robot prototype. The tests consisted of adjusting a potentiometer on a particular tag, which represented a certain execution speed. In each buoyage was performed by the positive and negative displacement, varying the speed in each test as the viability of the instrumentation, from the lowest to highest. In each test also is collected the data obtained through the ControlDesk and instrumentation (wattmeter, ammeter and voltmeter).

In each experiment was generated graphic of their displacement and later, in the stretch where the speed is constant, set a line. The line adjustment is needed to improve the fit of the static friction parameters, and when the acceleration is zero inertia can be neglected. Armed with the speed information (set straight), estimated the torque. For this, use information from the manufacturer about the performance of gearbox CA. As performed in any of the speeds the motor has exceeded 50% of maximum power used to yield (η) constant given by the product between the motor efficiency (74%) and gear (78%) in calculating the power mechanical.

Thus, a curve has been set (static friction map) from the found points and from the Eq. 2 (using the MatLab *nlinfit* function), according to Fig. 2.

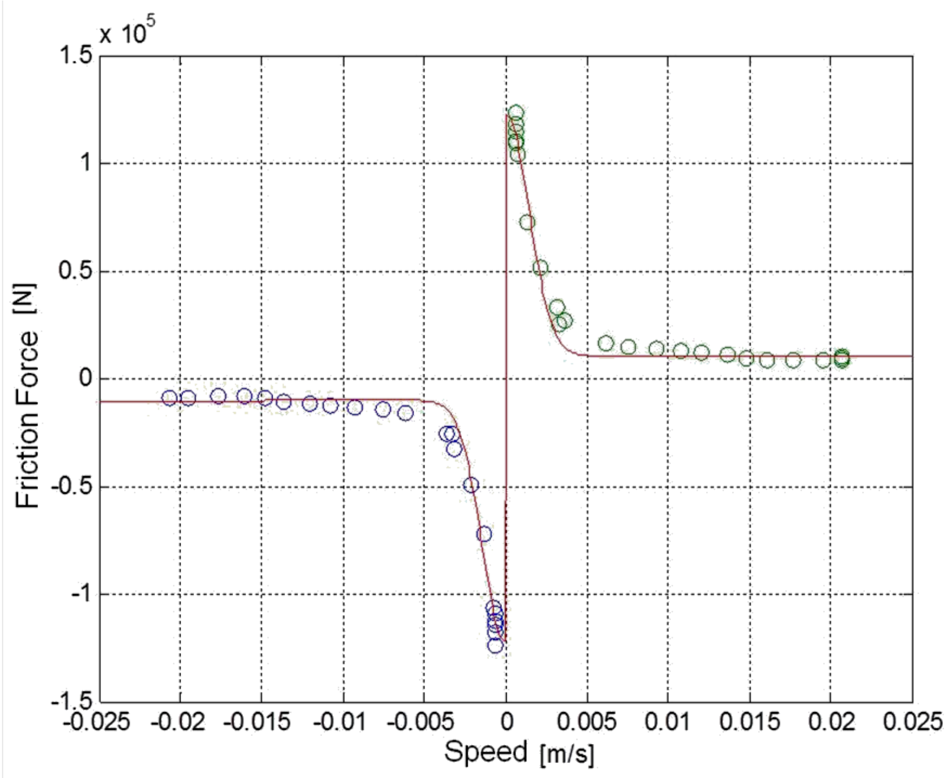

Figure 2. Friction Static Map Relating the Axis y the Force of Friction (F_{atr}) and in the Axis (x) the Speed ($\dot{y}_s$) in Steady State
Source: the author.

The parameters used in setting are shown in Tab. 1.

Table 1. Parameters for the Calculation of Characteristics of Friction
Source: the author.

Parameter	Description	Value	Unit
F_c	Coulomb friction coefficient	10300	N
F_s	Coefficient of static friction	12300	N
$\dot{y}_s$	Speed of Stribeck	0,002	m/s
σ_{2p}	Viscous damping coefficient positive	$3{,}2189 \cdot 10^3$	Ns^2/m^2
σ_{2n}	Viscous damping coefficient negative	$1{,}5277 \cdot 10^4$	Ns^2/m^2
M	Massa moved	11,250	kg
J_m	Moment motor shaft inertia	$1.2298 \cdot 10^{-5}$	kgm^2
M_{eq}	Equivalent mass	23,0530	kg

4. INCLUSION OF STATIC FRICTION MAP AND MODEL VALIDATION

When the movement is going on (in steady state), the mathematical model describing the movement, taking into account the dynamics of friction, can be written using Eq. 3 presented earlier. Considering the dynamic friction described in Eq. 2 and the parameters described in Tab. 1 (for the negative viscous damping coefficient when negative displacement) to make the simulation using Simulink/Matlab written from the block diagram shown in Fig. 3.

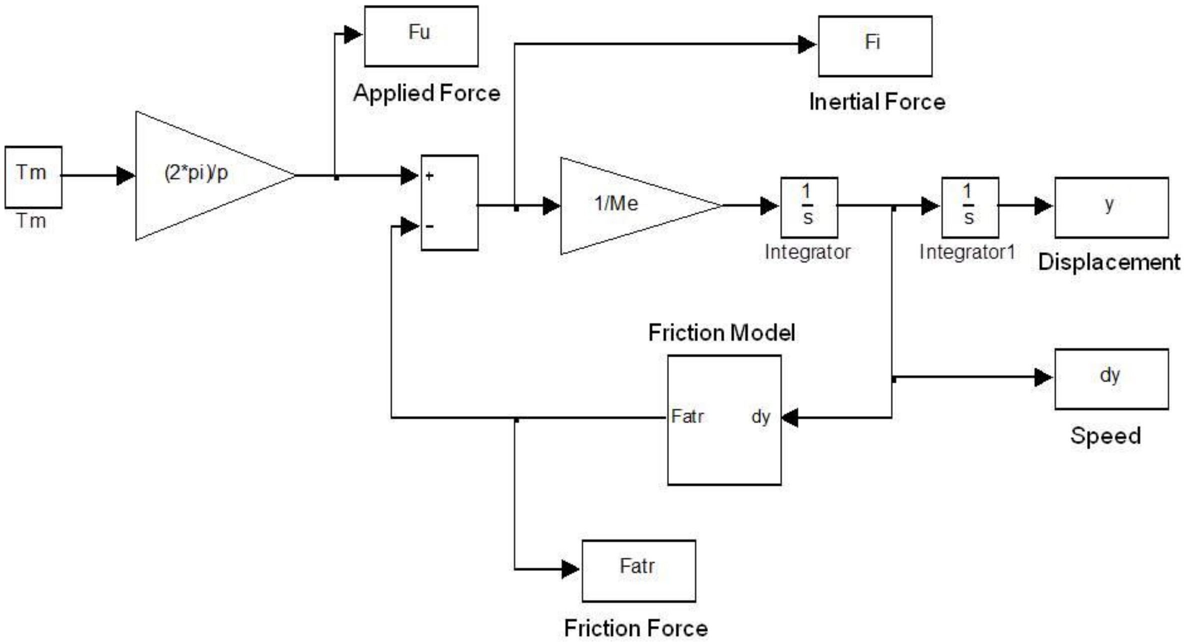

Figure 3. Mass Model Block Diagram Entering the Dynamic Friction
Source: the author.

where in the dynamic friction model, there is static friction map, described in Eq. 2 and written in the block diagram of Fig. 4.

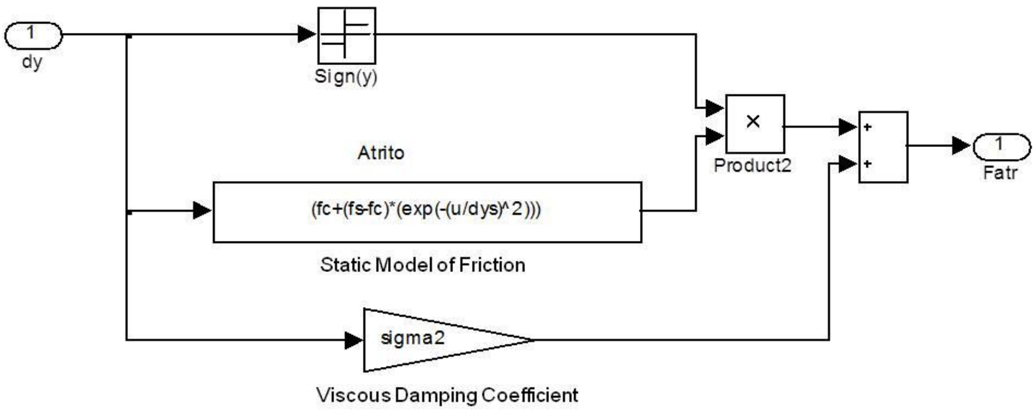

Figure 4. Dynamic Model of Friction LuGre
Source: the author.

Randomly, selected a simulation to validate the model. The Fig. 5 shows the experimental behavior and obtained by the mathematical model in the negative displacement.

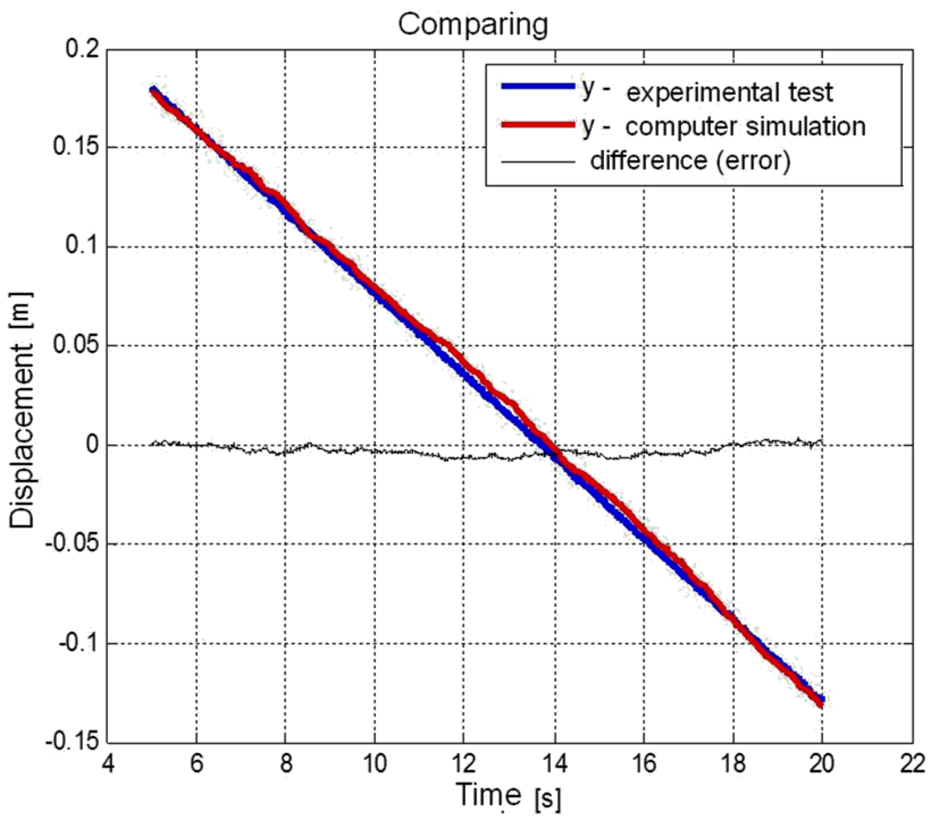

Figure 5. Displacement Negative for Dynamic Model Validation with Static Friction Map
Source: the author.

In Fig. 6 shows the validation of the model in the positive section.

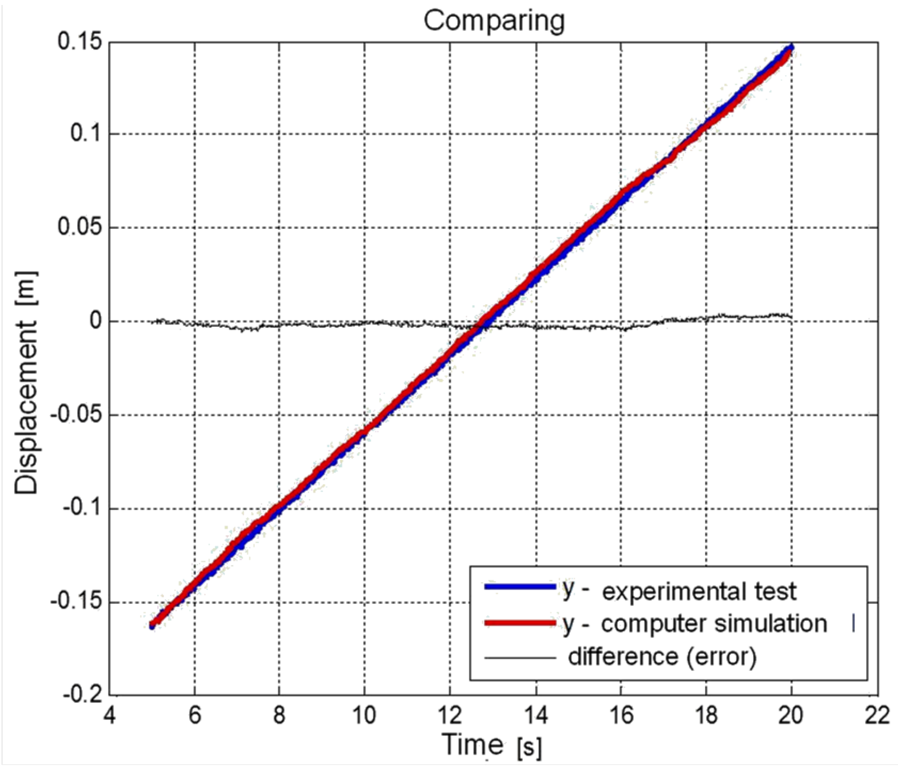

Figure 6. Displacement Positive for Dynamic Model Validation with Static Friction Map
Source: the author.

In comparison presented in Fig 5 and Fig. 6, between the experimental testing and computer simulation, it perceives that the model describes accurately the displacement and represents well the experiment.

5. CONCLUSIONS AND FUTURE PROSPECTS

This paper presented the identification of the friction characteristics through the static friction map in a prototype of a Gantry robotic joint, with the later inclusion and validation of the features in the dynamic model of the robotic joint.

The static friction map indicates the Coulomb friction characteristic is more relevant over the viscous friction agreed the literature. The results in open loop showed the validity of the model described, but for cases which require greater precision the other dynamic can be include/considered (how the backlash, for example) to improve the accuracy in the application, which may contribute to the development of more accurate control strategies and consequently, improving the quality of processes and contribute to the robot low cost in various applications such as woodworking and machining.

It is suggested to continue this work to include the electrical dynamic and the generalization/validation of the dynamic model for other degrees of freedom, besides the proposition and validation of control strategies in closed loop.

6. ACKNOWLEDGEMENTS

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