

# Verification of Precision-limit Positioning of a Direct Drive System with the Existence of Friction

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## Abstract

In this research, the verification of precision-limit positioning (PLP) of a direct drive system with the existence of friction is conducted experimentally. With regard to PLP, it means that the achieved positioning precision equals to the limit that the particular system hardware can offer. More specifically, in this research, the precision limit is defined to be the resolution of the sensor adopted for position feedback under the proved condition that all other parts of the system are capable of accomplishing this goal. PLP also enforces 100% repeatability when precision is of interest. Certainly, this is the limit of the precision that can be offered by a real positioning control system. But because of lacking of accurate knowledge about friction, especially the pre-sliding friction, PLP was not considered possible in the past. However, it has been shown in an earlier study that, with the help of newly revealed knowledge about pre-sliding friction, achieving PLP is possible. A simple and explicit criterion for the PID control design was also derived. In this research, such control design is applied to a direct drive DC torque motor system. Extensive experiments are arranged to observe the system performance. It has been shown that the repeatability of zero-count precision error is above 99.9996% according to more than 240,000 tests during a period of six months. Furthermore, all phenomena observed in these tests do coincide with what are expected by the friction model on which the PLP theory was based.

**Keywords** : Precision-limit Positioning, Direct Drive System, Pre-sliding Friction

## 1. Introduction

High precision positioning is a technology driver in the field of manufacturing. However, the task of positioning with extremely high precision was considered a difficult problem in the past because of lacking of accurate knowledge about friction, especially the pre-sliding friction. Therefore, when high precision is demanded in a positioning system, people usually use specially designed hardware and/or complicated control algorithms to reduce or compensate friction effects. Most of these approaches do improve the performance of positioning. But without thoroughly understanding the dynamics of pre-sliding friction, the system

performance can not be guaranteed. Nevertheless, it has been shown in an earlier study [1] that, with the help of newly revealed knowledge about the pre-sliding friction, a positioning system can achieve the goal of zero-count error with 100% repeatability when a digital encoder is adopted for position feedback. With regard to this goal, a new term, precision-limit positioning (PLP), is defined. Of course, this performance is under the proved conditions that all other parts of the system are capable of achieving this goal, and the driven load is kept constant. Certainly, this is the ultimate precision that a real positioning control system can achieve.

In the following section, the pre-sliding

friction dynamics will be briefly summarized. Its influence on positioning is discussed in section 3. An explicit stability criterion for PID control in the pre-sliding phase is also given in the 3rd section. Section 4 describes experiments for verification of PLP and is followed by a conclusion.

## 2. Pre-sliding friction dynamics [1]

A traditional well-known friction model is the Amonton-Coulomb model. According to this model, there is no displacement in the pre-sliding phase. However, in 1899, Steven [2], with the help of an interferometer, discovered that an elastic displacement does exist before the normal slip occurs. This small displacement can be ignored when the requirement of precision is not high. But when talking about the precision of sub micrometer or higher, the displacement in the pre-sliding phase must be considered seriously.

As the motion of the pre-sliding phase is referred, it is well known in the tribology field that the parameters of any friction model are both time and position varying. But actually, the parameters are temporarily time-invariant and locally position-invariant. By temporarily time-invariant it means that the parameters remain constant during a short time interval which is, however, long enough for positioning control purposes. Besides, locally position-invariant means that the parameters are unchanged if the system stays in the pre-sliding phase. Because of this important property, consistent and repeatable qualitative properties can be discovered; the motion in the pre-sliding phase consists of two kinds of motion. The first is a non-linear elastic deformation that demonstrates a special Preisach hysteresis which has memory and wiping-out effects of reverse points. The second

motion in the pre-sliding phase is plastic deformation which demonstrates creep and work hardening.

Based on these observations, a friction model consisting of several mechanical elements is established to match these qualitative properties. The parameters of this friction model can be treated as constants with “time-invariant” uncertainties. From the control point of view, PLP is thus possible. But it should be notified that 100% repeatable transient responses are not guaranteed.

## 3. Stability criterion of PID control in the pre-sliding phase

The widely accepted governing equation for a direct drive system is

$$m\ddot{x} + c_s\dot{x} = u - t_f \quad (1)$$

, where  $t_f$  is the friction force,  $u$  is the control input and  $c_s$  is the damping coefficient in the slip phase. Based on the traditional Amonton-Coulomb friction model, any point  $(x, \dot{x} = 0)$  in the state space is an equilibrium point when the control force  $u$  is less than the maximum static friction force. Therefore, the control force  $u$  can be released as the desired position, say  $x_d$ , is reached. However, this is not the case in a real positioning system. On the contrary, if a mass block is moved a small amount of distance in the pre-sliding phase, it will bounce back when the force is removed. This phenomenon is due to the retraction of the non-linear elastic deformation. Furthermore, once the plastic deformation has been work-hardened and no more creep can occur, the dynamic behavior of the system in the pre-sliding phase is very close to a mass-spring-damper system. The governing equation (1) is not valid anymore. Hence the real system is in fact composed of two different dynamic systems : a type-1 sliding system

and a type-0 pre-sliding system. Therefore, it is natural to take different control strategies for different phases to obtain a good response. The control design for coarse positioning in the sliding phase is well developed. So this research focuses on the fine position control in the pre-sliding phase.

In this phase, the system is basically a type-0 system. As a result, an integral type is needed for a zero steady state error. In this research, the controller structure of the pre-sliding phase is restricted to be a PID controller. It has been shown in [3] that the system is globally asymptotically stable about the desired position,  $x_d$ , if the following condition is satisfied :

$$k_i < \frac{(c + k_D)(\underline{h} + k_p)}{m} \quad (2)$$

,where  $k_p$ ,  $k_i$ ,  $k_d$  are the gains of the PID controller in the pre-sliding phase,  $m$  is the mass of the moving part,  $c$  is the damping coefficient of the pre-sliding phase, and  $\underline{h}$  is the smallest slope of the elastic deformation.

#### 4. Experimental verification and discussion

The system used in this research is shown in Fig. 1.

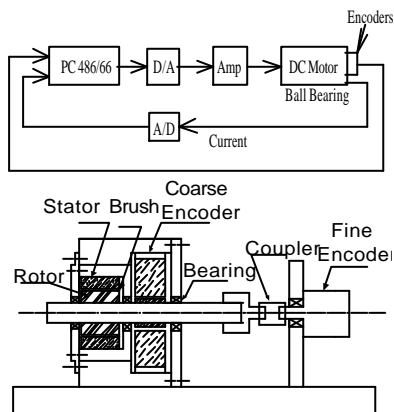


Fig. 1 The test platform

The plant is a direct drive DC torque motor mounted on ordinary ball bearings. The motor is driven by a linear amplifier. Two optical encoders with different resolutions, 86,400 counts/rev and 1,620,000 counts/rev, respectively, are mounted to measure the rotor position. The rotor angle is measured simultaneously by these two encoders. The outputs are compared to guarantee that the acquired data is correct. But only one encoder is used in the feedback loop in every test. The data acquisition and control is accomplished by a 486 PC with a D/A converter and an A/D one, each has a 12-bit resolution. The motor parameters such as moment of inertia and torque constant, etc., are identified using the method developed by Hsieh, etc. [4]

The stability of the two encoders used in this research is checked and the coincidence of data acquired from them is justified. This requirement is essential to get zero-count position error. The ratio of the readout of the coarse encoder to that of the fine one is fixed at 18.75. All other hardware parts in this system are also examined and verified to match the constraints mentioned in reference [3]. Hence the system is qualified for conducting PLP.

The verification of PLP consists of a series of batches of tests. 20,000 successive positioning tests are conducted in every batch. A total of 12 batches are accomplished during a period of six months. In addition to zero-count error test, every batch is arranged to verify some characteristics of the pre-sliding dynamics by assigning different positioning ranges and total time for each test. The time intervals between two successive batches are arranged from several hours to one month for testing the reliability of the system.

A typical result of the test is shown in the following figure.

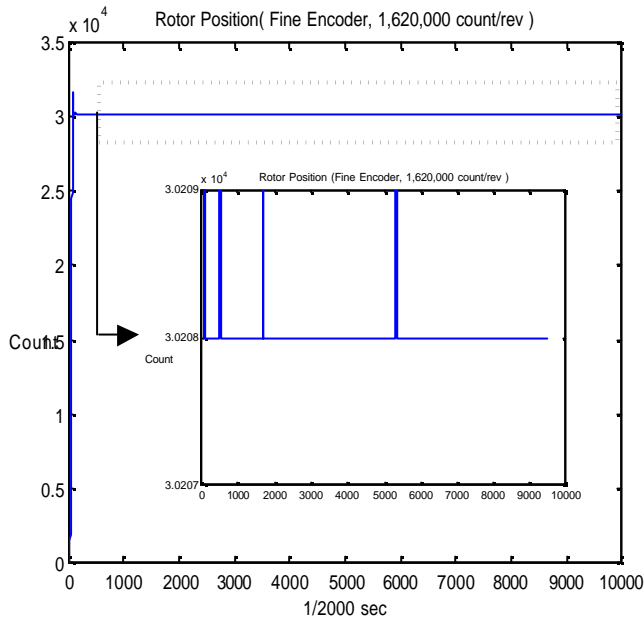


Fig. 2 Position response

The one count jerks that appear in single direction in Fig. 2 coincide with the plastic motion of the pre-sliding dynamics. [1] It is clear that the frequency of the jerks gets slower as the time goes by.

In this research, the settling time is defined to be the time when the position error reaches and stays within  $\pm 1$  count. Its value depends on the positioning range and has an average of about 0.2 sec if the motion range is 360 degrees.

In all these 240,000 tests, only one test failed to get zero-count error. As a result, the repeatability of zero-count steady state error is 99.9996%. After analyzing that failure, it is found that the stiffness of the elastic deformation dropped to a much smaller value suddenly. This phenomenon is related to a more subtle characteristic of friction and is out of the scope of this paper. However, it is quite rare and can be ignored in most cases.

## 5. Conclusion

Precision-limit positioning of a direct drive system with the existence of friction is verified experimentally. The results of this research have shown that the repeatability of zero-count position error is above 99.9996%. The phenomena expected by the pre-sliding friction model do coincide with those observed in these tests. Furthermore, the only one failure is fixed by changing the gains of the PID controller dynamically. Further one million positioning tests were conducted to achieve zero-count error positioning successfully with the modified controller. This implies that the pre-sliding friction model and the PLP theory presented in [1] and [3] are quite precise.

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## Reference

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