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Application in prestiction friction compensation for angular velocity loop of inertially stabilized platforms

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Abstract To overcome the influence of the nonlinear friction on the gimbaled servo-system of an inertial stabilized platforms (ISPs) with DC motor direct-drive, the methods of modeling and compensation of the nonlinear friction are proposed. Firstly, the inapplicability of LuGre model when trying to interpret the backward angular displacement in the prestiction regime is observed experimentally and the reason is deduced theoretically. Then, based on the dynamic model of direct-drive ISPs, a modified LuGre model is proposed to describe the characteristic of the friction in the prestiction regime. Furthermore, the state switch condition of the three friction regimes including presliding, gross sliding and prestiction is presented. Finally, a composite compensation controller including a nonlinear friction observer and a feedforward compensator based on the novel LuGre model is designed to restrain the nonlinear friction and to improve the control precision. Experimental results indicate that compared with those of the conventional proportion–integration–differentiation (PID) control method and the PID plus LuGre model-based friction compensation method, the dwell-time has decreased from 0.2 s to almost 0 s, the position error decreased to 86.7% and the peak-to-peak value of position error decreased to 80% after the novel compensation controller is added. It concludes that the composite compensation controller can greatly improve the control precision of the dynamic sealed ISPs.

1. Introduction

Inertially stabilized platforms (ISPs) are routinely used on vehicles, ships, aircraft, and spacecraft for diverse missions including aerial photography, battle reconnaissance, antenna stabilization, and missile guidance. An ISP is a mechanism, typically involving gimbal assemblies, for controlling the inertial orientation of its payload. A properly designed ISP precisely controls the sensor line of sight (LOS) despite intentional maneuvers, inadvertent motion, and additional disturbances. Although

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requirements for ISPs vary widely depending on the application, they have a common need of improving the stabilization precision. In some typical applications the precision is extremely high. For example, the stabilization performance of ISPs in surveillance and reconnaissance missions is now below 50 microradians (μrad); Inter-satellite laser communication may require 1 μrad; the Hubble space telescope points at distant stars and galaxies within a few milliarcsec, which is equivalent to looking at a dime from 200 miles away.[1]

Controlling LOS entails two equally important requirements. The LOS must be pointed in preselected or scenario-dependent directions toward a given target or target region and must be held steady in inertial space along the selected orientation. Although careful electromechanical design process will usually be carried, numerous sources of torque disturbances such as friction, spring flexure, imbalance effects, vehicle motion coupling and so on can act on a real mechanism causing excessive motion or jitter of the LOS. Unfortunately, in typical operation state of most applications is the so-called low-speeds and reciprocating motion state. In this situation, friction becomes a major disturbance source and limits the improvement of precision. To eliminate or restrain the influence of friction, the accustomed method is to reduce the friction itself. But in most ISPs this method is un-adopted, to make the situation worse, some dynamic seal arrangements inevitably introduce additional large friction in the system. On the other hand, due to the limit of size and weight of ISPs, the torque of motor is usually relatively small.

Therefore, an optional manner to improve the precision is to adopt effective friction compensation algorithms. The validity of this method obviously depends on the friction model. Many researchers have proposed a number of models based on different experimental observations. These models can be divided into static and dynamic friction models. Static friction models only characterize the frictional behavior in the macroscopic static and the gross sliding regimes.[2–5] The main problem of these models is the lack of description on zero angular velocity, which will cause inaccurate compensation when the motion crosses zero-state. The dynamic friction models focus on modeling the frictional behavior in both the presliding regime and the gross sliding regime,[6–14] which characterize the friction in low-speed better. On the other hand, many recent researches have been done benefitting from the advantages of the LuGre model in the field of servo control. A dual-observer based on the LuGre friction model is developed to improve the performance of trajectory tracking for gun servo system.[15] To improve the angular velocity tracking accuracy, the control scheme of LuGre model-based feedforward compensation is applied, which shows better control performance than the single angular velocity loop control.[16] On the other hand, disturbance observer (DOB) is a widely recognized control technique. DOB is capable of fulfilling the fundamental objectives in the feedback system design: robust stability and disturbance rejection.[17,18] However, the nominal model is difficult to obtain with the effect of the nonlinear friction.

Recently, a special frictional behavior is observed by Bazaei and Moallem.[19] The phenomenon shows the motor may not stop as soon as the angular velocity vanishes and a considerable backward angular displacement occurs before final stiction. Bazaei and Moallem[19] firstly succeeds in modeling such phenomenon by introducing the prestiction regime. Nevertheless, due to the difficulty of parameter identification for the friction model, the model is limited to apply in industry control systems.

In this article, the issues of friction modeling and compensation in the angular velocity loop of ISPs are studied. At first, the special behavior of the prestiction regime is introduced and the problem when using the LuGre model in characterizing such behavior is discussed. Based on the analysis, a modified version of LuGre model is proposed for dynamic friction compensation, in which the frictional regimes are divided into the presliding regime, the gross sliding regime and the prestiction regime. A time-varying function is developed to characterize the friction in the prestiction regime. The friction compensation strategy based on the proposed friction model is presented to improve the precision of velocity tracking in the existence of relatively larger nonlinear friction torque. The proposed friction compensation algorithm, along with the friction compensation using the LuGre model and the PID control, is tested on an experimental platform of an ISP with dynamic seal. Comparative experimental results are presented to illustrate the effectiveness of the proposed friction model-based friction compensation in practical applications.

2. Dynamic model of direct-drive ISPs

This paper deals with the direct-drive ISPs as a case study. The system dynamic can be simplified by

$$\begin{cases} J\ddot{\theta} = K_{\mathrm{m}}u - f \\ v = \dot{\theta} \end{cases} \tag{1}$$

where J is the total moment of inertia of the motor system, θ the angular position, K_{m} the motor constant, u the applied control signal, v the relative angular velocity and f the friction force. To ensure the manipulated commands proportional to the applied torque, the current closed-loop is employed in the motor driver. Due to the fast response ability of current loop, the current fluctuation caused by the ripple torque and the back electromotive force can be rejected. Therefore, for simplicity of presentation, the effect of the ripple torque and the back electromotive force is not explicitly considered. Furthermore, the implementation of friction compensation in the angular velocity servo control loop of ISPs is mainly concerned.

3. Problem formulation and modified LuGre model

For control applications, it is attractive to use a simple model that captures the essential properties of friction. The LuGre model contains only a few parameters and can characterize the dynamic behavior such as presliding displacement, hysteresis and varying break away force. The model has passivity properties that are useful for designing friction compensators that give asymptotically stable closed-loop systems.[6] According to the LuGre model, the friction force is described by

$$f = \sigma_0 z + \sigma_1 \dot{z} + \sigma_2 v \tag{2}$$

$$\dot{z} = v - \frac{\sigma_0 |v| z}{g(v)} \tag{3}$$

$$g(v) = F_{\mathrm{c}} + (F_{\mathrm{s}} - F_{\mathrm{c}})\mathrm{e}^{-\left|\frac{v}{v_{\mathrm{s}}}\right|} \tag{4}$$

where z denotes the average deflection of bristles, F_{c} the Coulomb friction, F_{s} the stiction force, v_{s} the Stribeck angular