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An experimental investigation of the effects of the compliant joint method on feedback compensation of pre-sliding/pre-rolling friction

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ABSTRACT

Mechanical bearings (i.e., sliding and rolling bearings) are widely used for motion guidance in precision positioning stages due to their low cost, large motion range and high off-axis stiffness. They are also finding increasing use in ultra-precision positioning, e.g., for low-cost and long-range nanopositioning in vacuum environments. However, mechanical-bearing-guided motion stages suffer from nonlinear pre-motion (i.e., pre-sliding/pre-rolling) friction which adversely affects their precision and motion speed in both tracking and point-to-point positioning applications. A compliant joint method has recently been proposed for simple, accurate and robust feedforward compensation of pre-motion friction in tracking motions, with excellent results. This paper experimentally investigates the influence of the compliant joint method on feedback compensation of pre-motion friction, which is critical to achieving fast settling in point-to-point positioning. It shows using a model-free (PID) controller that, for the same feedback gains, the mechanical-bearing-guided motion stage equipped with compliant joints exhibits much more linear closed loop dynamics and higher bandwidth compared to the traditional motion stage without compliant joints. The compliant-joint-equipped stage also has much faster settling time in point-to-point positioning experiments for most step motions tested, except for one particular step size where it settles slower than the traditional mechanical-bearing-guided motion stage due to the compliant joint dynamics. With the addition of an inverse-model-based disturbance observer to the PID controller, the settling time of the stage with compliant joints becomes uniformly much faster than the traditional mechanical-bearing-guided motion stage; its robustness and stability margins are also shown to be superior to those of the traditional mechanical-bearing-guided motion stage.

1. Introduction

Mechanical bearings (i.e., sliding, and especially, rolling bearings) are the most cost-effective bearing types used in motion stages [1,2]. Accordingly, mechanical-bearing-guided motion stages are widely used in precision applications due to their large motion range, high off-axis stiffness and excellent in-position stability [1,2]. Mechanical-bearing-guided motion stages are also very attractive as low-cost alternatives to air bearing stages for a wide range of ultra-precision applications. For instance, they are currently the only commercially viable option for a growing number of long-range nanopositioning applications that require vacuum compatibility [2,3].

However, mechanical-bearing-guided motion stages experience nonlinear pre-motion (i.e., pre-sliding/pre-rolling) friction which adversely affects their positioning precision and speed [2,4–13]. In the pre-motion regime, friction behaves as a nonlinear spring due to elastoplastic deformations and micro-slip of their inherent rolling elements, end seals and wipers [2,4,5,10–12]. PID-type feedback controllers (e.g., PID, P-PI, PI-P, etc.), widely used in practice, often encounter difficulties when trying to overcome the highly varying stiffness of pre-motion friction [2,4,5,13–16]. For example, during point-to-point positioning, the stage is commanded to travel to and settle within a pre-specified vicinity (window) of a target position as fast as possible. Pre-motion friction dominates as the stage approaches its target position, leading to very sluggish settling performance [2,4,10,11,13]. Such long settling times severely hamper motion speed. Similarly, during tracking applications (e.g., circular tracking or triangular scanning), large position errors (glitches) often occur as the feedback controller tries to overcome pre-motion friction at motion reversals, jeopardizing motion precision [8,9,12].

To deal with these problems, PID-type controllers must have high gains (i.e., high-gain feedback) in order to quickly overcome the large stiffness of pre-motion friction (during settling or motion reversals) [4,14,15]. However, such high-gain controllers could easily lead to large overshoots, limit cycles and instabilities due to the rapid and nonlinear changes of pre-motion frictional stiffness during transient

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motions [2,5,16]. Therefore, model-based friction compensation methods are often used to mitigate the undesirable effects of pre-motion friction beyond what is achievable using model-free (e.g., PID-type) controllers; they can be executed in feedforward or feedback [5,8–12,17–21]. Feedforward friction compensation can significantly improve the tracking performance of mechanical-bearing-guided motion stages when the friction model employed is sufficiently accurate [8,12]. However, it is not effective in solving the slow settling problem caused by pre-motion friction during point-to-point positioning, because feedforward friction compensation depends on the desired velocity to predict and preemptively cancel out friction [2,10]. When a stage is trying to settle to a target position, the desired velocity is often zero, even though the actual velocity is not. Model-based feedback friction compensation approaches make use of the actual states (e.g., position and velocity) of the system to improve disturbance rejection, using disturbance observer [8,19,20], gain scheduling controllers [4,21], friction observers [17], etc. Because pre-motion friction is extremely nonlinear and variable (i.e., difficult to model accurately), stability and robustness issues often occur when using feedback friction compensation methods, thus limiting their practicality [2,5]. Adaptive control can enable a model-based feedback friction compensation controller to handle varying friction dynamics [18,19]. However, such approaches often suffer from convergence issues related to poor persistence of excitation from smooth reference commands commonly used in precision applications [5].

Apart from the abovementioned control-based friction compensation approaches, the undesirable effects of pre-motion friction can also be mitigated through design-based methods. This often involves mechanical modification of the traditional mechanical-bearing-guided motion stages. For example, a coarse-fine arrangement, where a “fine” flexure-bearing-guided motion stage is mounted on a “coarse” mechanical-bearing-guided motion stage, is sometimes used to improve the precision and speed of mechanical-bearing-guided motion stages [22–24]. However, this arrangement makes the system more complex, bulky and expensive due to the additional physical components (e.g., extra sensors, actuators and control hardware) [25,26]. Alternatively, Dong et al. [2] have proposed an approach, called vibration assisted nanopositioning (VAN), to mitigate the slow settling problem of mechanical-bearing-guided motion stage using high frequency vibration (aka dither). Unlike traditional dithering techniques which could jeopardize the stage's precision by directly vibrating the stage or guideway [27,28], VAN is able to improve the settling performance of mechanical-bearing-guided motion stage without vibrating the stage, thus maintaining high precision. However, the need for additional costly actuators (e.g., piezo actuators and voltage amplifiers) to induce vibrations could limit the practicality of the VAN approach. A recent paper [29] by the present authors has proposed a new design-based approach, called the compliant joint method, which is simpler (and more cost-effective) compared to coarse-fine arrangements and VAN. The paper [29] shows that pre-motion friction can be accurately and robustly compensated in feedforward using simple friction models by attaching the bearing to the moving table using a joint that is very compliant in the motion direction. Superior performance and robustness of a simple feedforward friction compensation scheme combined with the compliant joint method has been experimentally demonstrated through circular tracking motions with different radii and velocities [29,30]. However, the influence of the compliant joint method on feedback compensation of pre-motion friction of mechanical-bearing-guided motion stage, which is critical to improving settling performance in point-to-point positioning, has not been explored.

The key contribution of this paper is in carrying out a rigorous experimental investigation into the effects of the compliant joint method on feedback compensation of pre-motion friction, hence its ability to improve settling performance of mechanical-bearing-guided motion stage in point-to-point positioning. Specifically, after a brief overview of the compliant joint method and description of the experimental set-up in Section 2, the paper:

1) Shows in Section 3 using a PID controller that, for the same feedback gains, a mechanical-bearing-guided motion stage equipped with compliant joints (i.e., compliant stage) exhibits much more linear closed loop dynamics and higher bandwidth compared to a traditional mechanical-bearing-guided motion stage without compliant joints (i.e., rigid stage). Moreover, the compliant stage settles much faster in point-to-point positioning for most step motions tested, except for one particular step size during which it settles much slower than the rigid stage due to the dynamics of the compliant joints.
2) Demonstrates in Section 4 that with the addition of an inverse-model-based disturbance observer (DOB) to the PID controller, the compliant stage achieves uniformly much faster settling time than the rigid stage; its robustness and stability margins are also shown to be superior to those of the rigid stage.

This is followed by conclusions and future work in Section 5.

2. Overview of compliant joint method and experimental set-up

2.1. Compliant joint method

Friction behavior can be divided into two regimes: macro- and micro-displacement regimes [2,4–7,10–12,29,30]. They are sometimes also referred to as the gross motion and pre-motion friction regimes, respectively, where “motion” implies sliding and/or rolling [10–12]. In the gross motion regime, friction is mainly a function of the relative

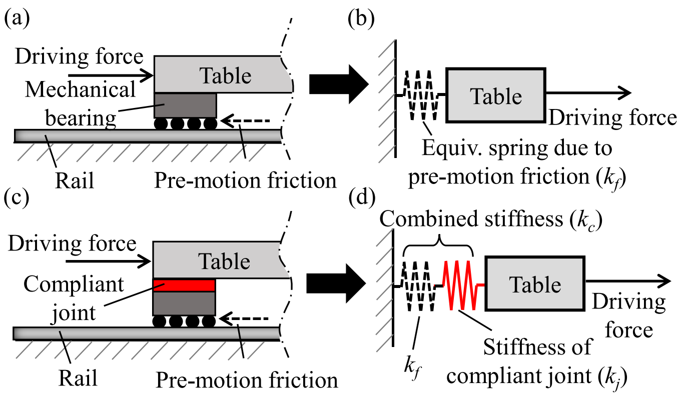

Fig. 1. (a) Schematic of a mechanical-bearing-guided motion stage with the bearing: (a) rigidly attached to the table (i.e., rigid stage), and (c) attached to the table using the compliant joint (i.e., compliant stage); (b) and (d) are equivalent spring models of (a) and (c), respectively.