CONTENT

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Friction compensation in ultrahigh-precision positioning

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Abstract

Ultrahigh-precision positioning devices are essential in precision engineering and microsystems' technologies. As they need to allow sub-micrometric or even nanometric displacements, their nonlinear frictional behaviour, induced by a number of sliding and rolling components, has to be efficiently compensated for. If a model-based approach is followed, suitable modelling of such disturbances, which is generally performed using state-of the art friction models, has to be performed. An overview of different compensation and control algorithms applied to ultrahigh-precision positioning systems is hence given in this work.

Keywords: *friction compensation, ultrahigh-precision, precision engineering, microsystem technologies, control algorithms*

1. Introduction

Ultrahigh-precision positioning systems are important devices in microsystems' technologies and precision engineering in general, and particularly in machine tools, optics, robotics and production of semiconductors [1]. Such devices typically enable achieving positioning precisions in the micrometric or even nanometric domains. Due to a number of sliding and rolling machine elements in relative motion, these mechatronics systems are usually subject to different nonlinear dynamical effects that negatively affect their positioning performances. The dominant disturbance in this frame is the time-, position- and temperature-dependent friction, with its nonlinear stochastic characteristics. Frictional disturbances have thus to be compensated for via appropriate control algorithms. If a model-based approach is followed, the first crucial step is to properly model frictional disturbances and then, based on the required positioning performances, implement appropriate control algorithms. The majority of available literature suggests that the frictional behaviour can be represented by friction models that consider two typical motion regimes: gross sliding and pre-sliding. Recent studies show, however, that these models could be improved further by extending them to the nanometric domain [2]. There are also some emerging non-model based approaches, which could be efficiently used in some of the considered cases.

Various friction compensation techniques and control algorithms for precision positioning devices are hence presented in this work. These approaches are briefly introduced, their main characteristics and performances are described, and experimental results from previous work of the same authors are presented and discussed.

2. Friction modelling

Friction effects are usually referred to two motion regimes in the literature: the pre-sliding and the (gross) sliding regime. Recently, experiments shownhave shown that ultrahigh-precision positioning certainly happens in the pre-sliding motion regime. It is thus important to account for this effect when developing suitable model-based control methods [1].

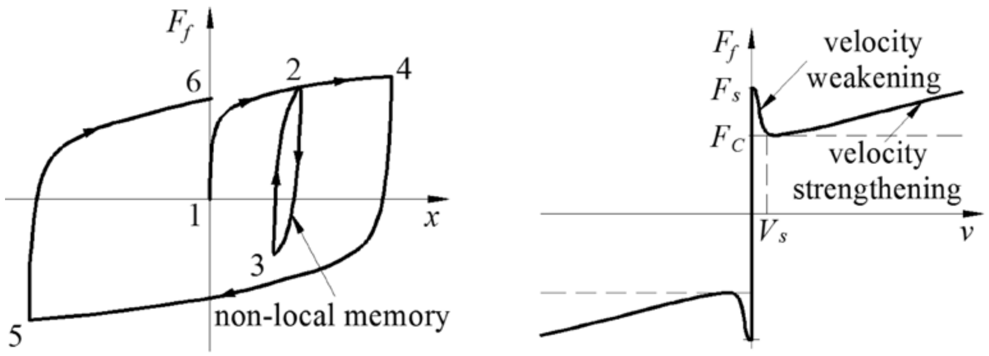

Fig. 1. Friction in the pre-sliding (left) and in the sliding (right) motion regimes

The pre-sliding motion regime is characterized by an elastoplastic nonlinear behaviour with hysteresis that depends on normal and tangential forces as well as on the history of motion (Figure 1 left). What is more, hysteresis is characterized here by non-local memory, i.e., an input-output relationship such that, when there are multiple displacement reversals, at each closure of the inner loop, the curve of the outer loop is followed again [3]. It should be noted that the frictional behaviour at the nanometric level [2] is treated in detail in a separate contribution below, and will thus not be considered further in the examples presented in this work.

In the pre-sliding motion regime, friction is a function of displacement rather than velocity. As the displacement increases, friction becomes a function of velocity, i.e. enters the sliding motion regime where it is characterized by static friction, Coulomb friction and viscous friction, i.e., it can be described by the conventional Stribeck friction curve (Figure 1 right).

The described frictional effects can be characterized by different state-of-the-art friction models [3-4]. One of the most comprehensive and widely used friction models is the Generalized Maxwell Slip (GMS) model [5] (Figure 2). This model enables taking into account both motion regimes and all the important frictional effects depicted in Figure 1, and can hence be used for model-based control schemes that are suitable to achieve ultrahigh-precision positioning. In order to apply such a model to precision positioning system, their characteristic parameters have, however, to be identified experimentally. A detail description of the experimental procedure aimed at the identification of frictional parameters is given in [1, 4].

3. Compensation strategies

In the following sections, different friction compensation approaches, some of them being model-based and some non-model based, are presented.

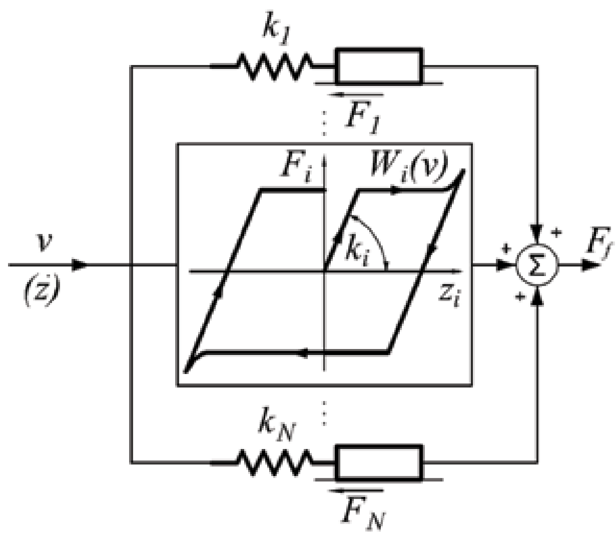

Fig. 2. The GMS friction model

3.1. Conventional PID control and the feed-forward approaches

The PID controller is a widely used control approach in many industrial environments. This feedback control method multiplies the value of the error, determined as the difference between a set-point and the process value, by proportional, integral and derivative gains commonly determined via a trial-and-error procedure or the Ziegler-Nichols tuning rules [3]. The PID controller gains are typically tuned for a determined motion regime and cannot, therefore, assure the same level of accuracy for different motion amplitudes. What is more, the optimal PID gains can vary even for the same motion amplitude, but in different positions on the considered motion mechanism. It is thus obvious that, although PID controllers allow building control laws even without developing a complete mathematical model of the positioning system, generally they do not allow compensating efficiently for the effects induced by frictional disturbances [3].

Since PID-based control approaches cannot, thus, account for stochastic frictional effects present in ultrahigh-

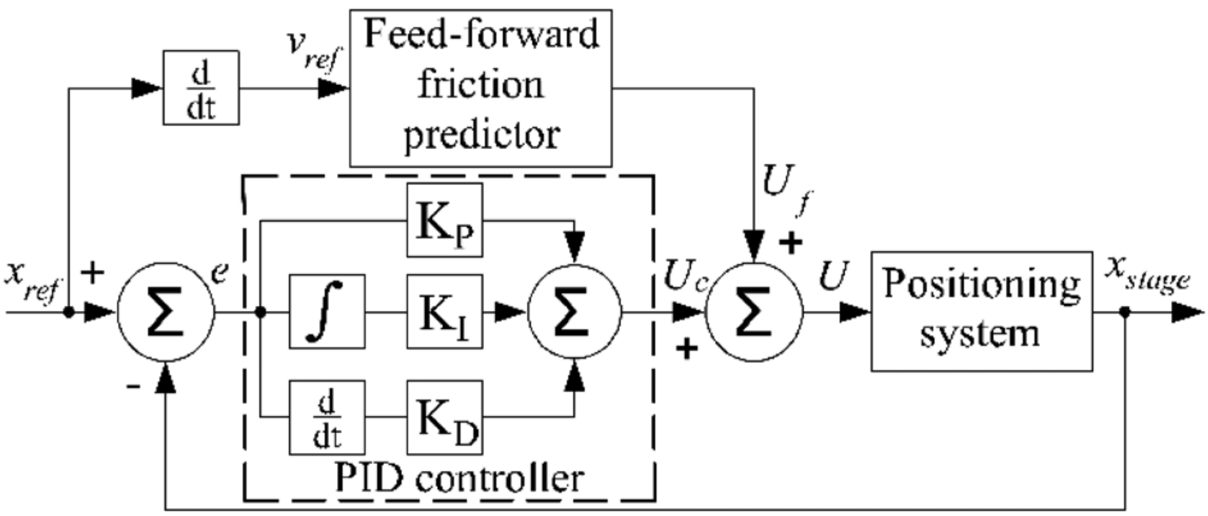

Fig. 3. The control algorithm based on feed-forward compensation of frictional disturbances and a PID

precision positioning systems, PID can be enhanced by employing an additional feed-forward term, which is based on the friction model of the system (Figure 3) [3]. It was, in fact, recently shown that a conventional PID controller, complemented with a feed-forward term based on the Generalized Maxwell-slip friction model, guarantees positioning performances in the sub-micrometric domain. On the other hand, however, the real-time implementation of the resulting controller can be quite challenging [3].

3.2. Cascade control

Cascade controllers are typically made of two PI controllers in series, one of which closes the velocity and the other one the position loop. It was experimentally shown that the cascade control can be efficiently used for positioning control, although the tuning of the parameters of two PI controllers can be difficult as well as computationally quite intensive [6]. This limits the execution time, which directly affects systems' dynamic response. As in the case of the PID controller alone, another disadvantage of this approach is that its gains are typically tuned for a certain motion regime and/or a certain position on the considered motion mechanism, and therefore it cannot assure the same level of accuracy for different motion amplitudes and/or different positions.

3.3. Model reference adaptive control

The aim of the work performed in [7] was to develop a model-based adaptive control approach based on pulse width modulation (PWM). The coefficient of proportionality between the pulse width and the respective displacement is determined here adaptively by using the model reference adaptive control (MRAC) algorithm (Figure 4). The resulting displacement of the system, based on the characteristic equation implemented in the regulator, is hence determined by a parameter adaptation algorithm (PAA).

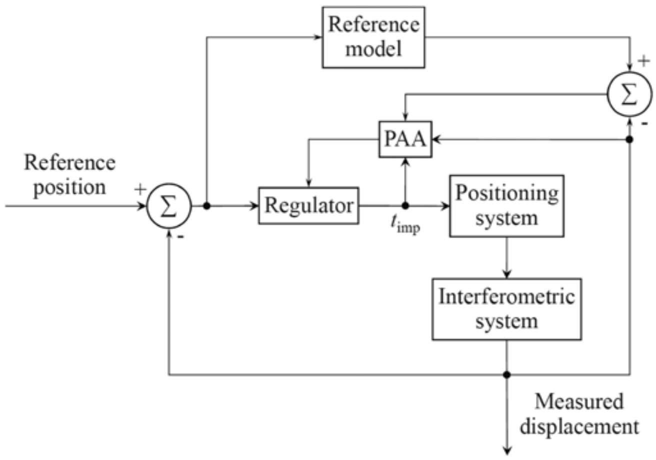

Fig. 4. Model reference adaptive control approach

In [7] it was shown that, for pulse widths of 200 ms or less, i.e., for high-precision (pre-sliding) displacements limited to approximately 10 µm, a proposed quadratic relation describes excellently the behaviour of the used positioning system. When displacement amplitudes larger than the limit of validity of the quadratic relation are needed, a simple P control is then used to bring the stage within the range of validity of the MRAC, i.e., the overall positioning algorithm is structured as a dual control algorithm. In the experimental validation, the developed approach allowed obtaining positioning performances in the sub-micrometric domain. However, its applicability is limited not only by the characteristic marked overshoots of the P controller, but particularly by a considerable lowering of the positioning speed, especially for longer travel ranges, when a suitable switching element between the P and the MRAC-based PWM has to be used [7].

3.4. Self-tuning regulators

In the set of available adaptive nonlinear control schemes, self-tuning regulators (STR) are a viable and simple solution for stochastic systems. An example of such a controller is a self-tuning PID controller whose gains are tuned online based on the theory of adaptive interactions (Figure 5).

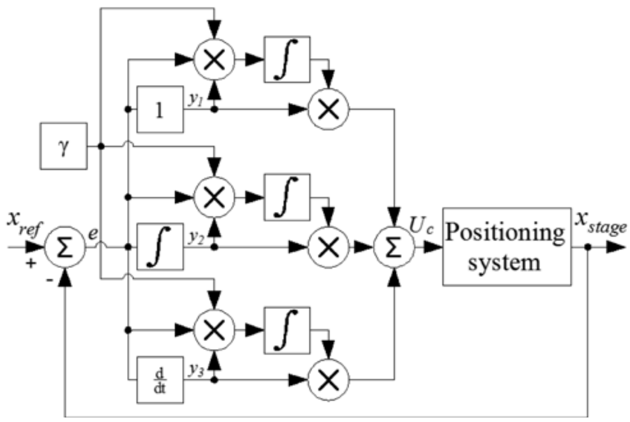

Fig. 5. PID self-tuning regulator block-diagram

In its simplified form, the STR algorithm does not depend on the plant model, while the adaptation of the parameters of the regulator can be reduced to an algorithm based on a single adaptation coefficient γ. Experiments show that, although this algorithm is able to guarantee very small steady-state errors, in point-to-point positioning it can induce quite large overshoots (Figure 6) [3].

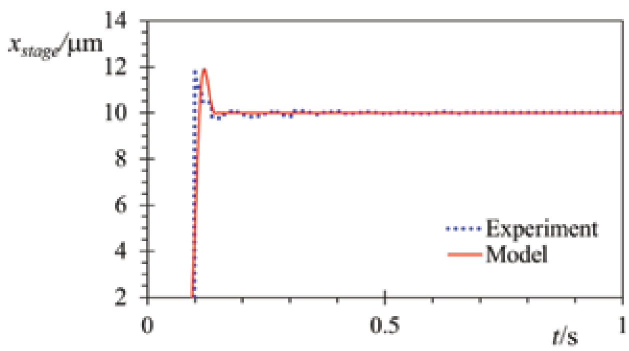

Fig. 6. Point-to-point performances of a precision positioning system controlled via an STR approach

3.5. State-space control methods

In [6] a state-space controller based on a vector with two gains is synthetized by using the pole placement method, i.e., by employing Ackerman's formula with an additional gain used to minimize steady-state errors. The positioning performances of such a controller are compared to that of the PID and of the cascade regulators (Figure 7). It was hence concluded that this control algorithm allows lowering the overshoot and the rise time compared to those attained via the PID and the cascade control methods.

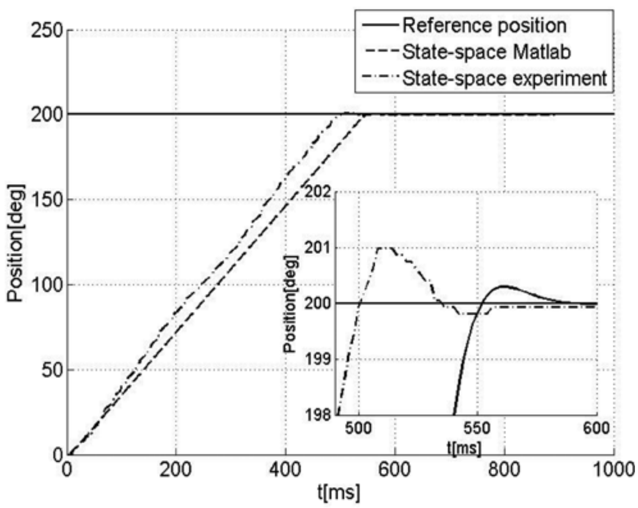

Fig. 7. Performance comparison for different algorithms

It is to be noted in this frame that, if the state-space model of the system is known, other methods, such as the linear quadratic regulator (LQR) or the model predictive control (MPC), could be employed to obtain the vector of gains.

Besides using a classical approach to build the system's state-space model, i.e., by writing the respective differential equations as described in [6], a data-driven approach can also be followed, as it will be shown in the following section.

3.6. Koopman Model Predictive Control (MPC)

The Koopman operator represents a mathematical tool that can be applied to estimate the behaviour (i.e., the future states) of a nonlinear dynamical system. Recently the Koopman operator, whose numerical approximations allow "lifting" the nonlinear dynamics of the considered device (i.e., of its state-space model) into a higher dimensional space - where its behaviour can be accurately predicted by a linear system, was, in fact, successfully extended to controlled dynamic systems [8] and applied to ultrahigh-precision positioning [9].

What is particularly important is that this scheme does not require the mathematical description of the observed system, i.e., it is completely data-driven, and therefore it reduces to a nonlinear transformation of the data (the lifting) and a linear least squares problem in the lifted space. What is more, such linear predictors have shown superior prediction performances compared to e.g. local linearization procedures. The obtained predictors have been then recently also successfully used in the design of Model Predictive Controllers (MPCs) for nonlinear dynamical systems, with the resultant computational complexity comparable to that of MPCs for linear dynamical systems [8-9]. The same approach can then be also used to design other types of controllers, such as, for example, the Linear Quadratic Regulator (LQR) or the H-infinity method (H∞), again based on the state-space model built from measured data only. In fact, MPCs are an emerging class of algorithms based on an iterative optimization of the model of the considered devices subject to constraints, by allowing the time frame of the behaviour of the device to be extended to a finite future time horizon (prediction), which is increasingly used in industrial settings.

The Koopman operator is therefore applied in [9] to track the position of an ultrahigh-precision positioning device. The open loop response of this system, obtained for a random input, is depicted in Figure 8. It can thus be seen that the Koopman operator allows obtaining a state-space model of the system that follows very accurately the real dynamics of the system.

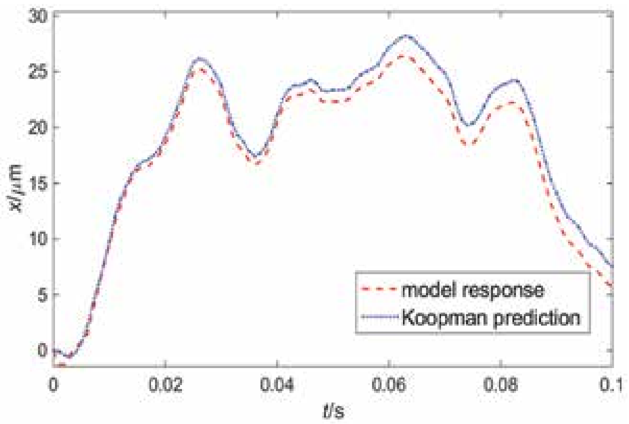

Fig. 8. Prediction of the Koopman-based model of the behaviour of an ultrahigh-precision positioning system

A further investigation of the closed-loop responses of the system controlled with different approaches was performed [9]. In the first set of experiments, the positioning device follows a sinusoidal trajectory (Figure 9).

It can hence be seen that the largest tracking error is induced by the PID controller. When PID is complemented with a feed-forward (FF) term, the tracking error is reduced, but the parameters of the PID have still to be adapted to each amplitude and/or frequency change, while the slow dynamics of the controller limits its real-time implementation. When STR and Koopman MPC are used instead, the tracking errors are significantly reduced in all considered cases. It is evident, however, that STR tracks somewhat better the reference signal at direction reversals, whereas the

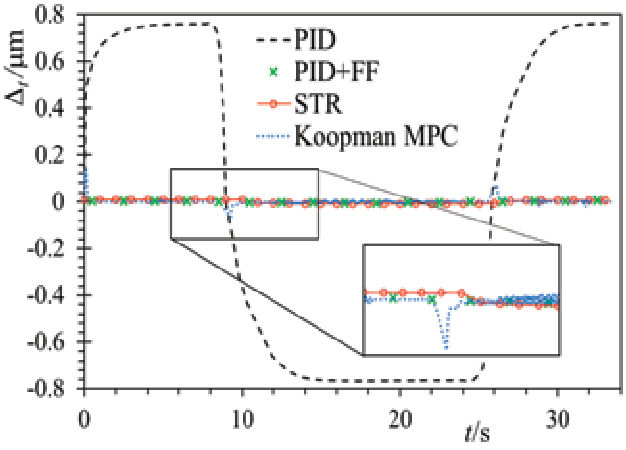

Fig. 9. Tracking errors for different control approaches

employment of the Koopman-based MPC controller induces small "glitches". It must be pointed out, however, that in the studied case the lifting map was a simple delay embedding, whereas a more elaborate choice of this map could potentially eliminate this problem [9].

A second batch of experiments is related to point-to-point positioning for Koopman-based MPC, compared to STR data used here as benchmark (Figure 10). It can thus be clearly observed that for both the STR and the Koopman-based MPC the tracking errors are very low, but in point-to-point positioning Koopman-MPC outperforms STR PID in terms of lower overshoots and shorter settling times.

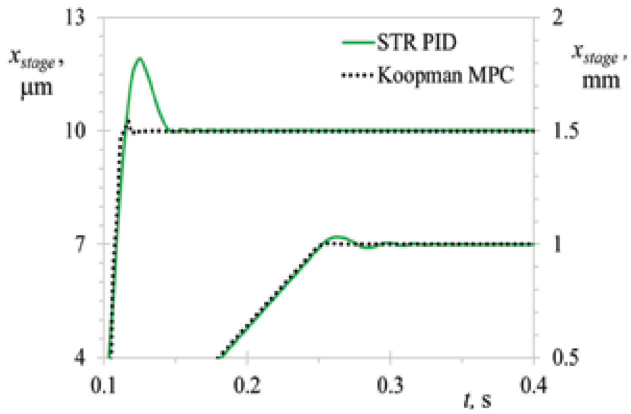

Fig. 10. Point-to-point positioning experiments for STR and Koopman-based MPC

The data-driven machine learning approach based on the Koopman operator theory was recently applied in modelling a complex pneumatically-driven soft robotic device as well. In that case, the comparison of experimental responses with those obtained from simulations on the obtained Koopman-based model, for different prediction steps, allowed establishing that the modelled responses follow again very accurately the experimental data. With the aim of allowing to attain a precise tracking control of the end-effector of the soft robotic device, the thus developed model will be used in future work to synthetize a completely novel motion controller [10].

4. Conclusions and outlook

Different friction compensation and control approaches used in ultrahigh-precision positioning devices, starting from the PID controller which is a widely used control approach in many industrial environments, and usually does not require the model of the system, are presented in this work.

Due to the fact that the PID control typology cannot account for stochastic frictional effects present in ultrahigh-precision positioning applications, it is often complemented with an additional feed-forward term, generally established as a friction compensator based on some of the state-of-the-art friction models such as the GMS description of friction. Although the PID + FF control approach can assure high precision and accuracy levels, its real-time implementation can be quite difficult.

Furthermore, two PI controllers in a cascade arrangement can be used. This approach cannot, however, account again for the stochastic nature of friction.

One of the viable solutions is then to resort to adaptive control typologies such as the model reference adaptive control (MRAC), which proved to be efficient for ultrahigh-precision positioning, but again at the expense of its difficult real-time implementation. An example of a relatively simple adaptive control algorithm in terms of its real-time implementation, is the self-tuning regulator (STR), which is proven to be very efficient in ultrahigh-precision positioning. On the other hand, however, STR can induce overshoots in point-to-point positioning.

It was shown next that control approaches based on the state-space model of the observed system can also be very efficient in precision positioning applications. It is generally very hard, though, to obtain the mathematical models of complex devices such as some of those commonly used in ultrahigh-precision positioning applications. A recently proposed data-driven approach, based on Koopman operator theory, can, in turn, be efficiently used in this case to build a state-space model of the system, based on measured data only. The procedure of constructing the respective control algorithm is then the same as for systems with mathematical models based on differential equations. The Koopman-based technique has been applied to ultrahigh-precision positioning and similar positioning performances as in the case of the STR controller are obtained, with a marked advantage in terms of decreased overshoots and settling times in point-to-point positioning.

Due to its proven efficiency, in future work the data-driven machine learning approach based on the Koopman operator theory will thus be applied to control the positioning performances of the end-effector of pneumatically driven soft robotic devices.

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