Precision Control of Planar Motion Stages(平面ステージの精密制御に関する研究)

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論文内容要旨

This thesis presents the design and implementation of the suggested precision control methods for the surface motor-based planar motion stage and the Sawyer motor-based planar motion stage.

Firstly, the general background and trend review of precision positioning technology and its applications are provided in Chapter 1. Precision positioning systems are fundamental components in industrial machines such as machine tools, measuring machines, laser processing and semiconductor manufacturing systems. Taniguchi's famous graph predicting machining accuracy has gradually become true with the increasing need for high precision machines and products at present. Although the difference between precision positioning and normal positioning is not defined by any organizations or institutes, many researchers studying in the related field, however, recognize that precision positioning systems are often desired to have the accuracy and/or resolution better than 1 μm, and ultra-precision positioning systems are often desired to have the accuracy and/or resolution better than 10 nm. High positioning accuracy and/or resolution is not the unique consideration when developing a precision positioning system. Fine dynamic performances such as high acceleration and high speed are also very important to meet the demand of current high speed machining. Moreover, the flexibility and simplicity of feed drives of the precision positioning system are also important because the feed drives of a machine tool decide the position and velocity of slides or axes in accordance with commands.

Recently, planar motor stages are being studied as next generation precision/ultra-precision systems which are fundamental components in industrial machines such as machine tools, measuring machines, laser processing and semiconductor manufacturing systems. A planar motion stage which is actuated by the planar motor(s) and can achieve the translational motions in an in-plane direction and/or a small yawing motion, possesses the advantages of direct drive, in-parallel actuation, non-contact levitated drive and simple structure compared with the conventional two-dimensional positioning device. However, this stage will consequently loses an advantage of using mechanical transmission, e.g. gear, ball- or lead-screw drives and so on which can provide transmission buffer for total system inputs, and becomes sensitive to modelling uncertainties and disturbances due to load changes, system parameter perturbation and force ripple, position measurement noise and high frequency error components generated from the amplifiers especially when a pulse width modulated amplifier is used. Moreover, there often exists coupling effect among the different drive axes of a multi-DOF planar motion stage, especially for the positioning systems levitated by air bearing or magnetic bearing. Thus, controllers based on classical control theory for planar motion stages can not achieve satisfied performance. From these viewpoints, in this study, for the purposes of investigating precision control of planar motion stages, two typical planar motion stages: the surface motor-based planar motion stage and the Sawyer motor-based planar motion stage are primarily constructed. These two stages are high-precision positioning systems being of multi-DOF motions in a XY plane. The surface motor-based planar stage is oriented for the applications of ultra-precision positioning (about 10 nm order positioning accuracy). The Sawyer motor-based planar stage is oriented for the applications of precision positioning (about 1 μm order positioning accuracy). Then in order to focus on the concerns of precision control strategies in planar motion stages, the dynamic modeling, numerical calculation, simulation and experiments are performed. Control approaches are mainly focused on the following aspects: 2-DOF PID control, decoupled control, sliding mode observer (SMO) based compensation and hybrid position-sensorless control.

In order to investigate the above control strategies on the target planar motion stages, firstly analysis and development of the primary dynamic models of these two planar motion stages have been carried out. Secondly, design and development of the above advanced control strategies have been performed. After simulation study, control strategies have been implemented by high performance DSP system. Finally, experimental verifications of nanometer and sub-micrometer level precision control on the planar motion stages have been done. Hopefully, this thesis can be a useful practical reference in the fields of precision control on planar motion stages or other similar precision positioning systems.

In Chapter 2, dynamics modeling, decoupled control design and performance evaluation for the surface motor-driven planar motion stage have been presented. After an overview of the stage and measurement sub-system, the analytical method combined with the step responses, is employed to construct the dynamics model of the stage. The surface motor-driven planar motion stage, however, is only physically restricted in the Z-direction by Z-bearing. As there are no X- and Y- bearings to restrict the stage in the X- and Y- directions, feedback control based on the measured XY-positions and the rotational motion about the Z-axis is vital for driving such a stage. It is also essential to build proper controllers so that the interference errors among the axes and other disturbances can be reduced for achieving a higher tracking accuracy and a better dynamics performance. Based on the identified model, a fine-tuned PID controlling element, cascaded by a notch filter for dealing with the stage resonance, is implemented. A decoupled control strategy and an effective disturbance observer are added to the designed PID controller to improve robustness and tracking performance of the stage system. From the results of the positioning experiments, it has been verified that the overall controller has good dynamic and tracking performances, especially the capability of reducing the interference between different drive axes. When the stage moves at a constant speed or a constant acceleration, the interference error can be reduced to ±0.05 μm in X- and Y- directions and ±0.1 arcsec in θ_z-direction, respectively, while for the conventional controller, these errors are ±0.2 μm and ±1.2 arcsec, respectively.

In Chapter 3, for precision positioning control of the surface motor-based planar motion stage being of a multi-input and multi-output (MIMO) plant, a novel control scheme combining general feedback control to achieve basic dynamic performance and SMO approach to estimate and compensate for modeling uncertainties and disturbances dynamically is developed. After some improvement of the stage compared with the stage used in the work of Chapter 2, dynamic modeling of the stage is performed again on the assumption that the influence of the small yawing motion on the electromagnetic characteristics of the stage can be neglected. The dynamics of the planar motion stage driven by multi-PMLMs can be viewed as two components: a dominant linear model and the modeling of uncertainties and disturbances. With respect to the construction of the planar motion stage and the principle of PMLM, modeling uncertainties include un-modeled dynamics and system parameter perturbation, and disturbances which are generated from load changes, force/torque ripple, nonlinear dynamics, plant interaction and other unknown inputs. As the presence of the uncertainties and the disturbances deteriorates the performance of the stage, the attention must be paid in the design of the control system for precision positioning. Overall control strategy is introduced and the design of SMO is discussed in detail. A state-space SMO has been tailored for the stage by invoking a discontinuous switch control to induce the sliding motion so that the plant can be insensitive and robustness with respect to the modeling uncertainties and the disturbances. An estimator function has been dedicated to deal with the output errors of the SMO so that the bounded uncertainties and the disturbances can be precisely estimated, and compensated dynamically in the inner-loop. The developed SMO has been added to a PID controller and this combination has yielded a robust control structure for the planar motion stage. The simulation and experimental results for confirmation of the effectiveness of the suggested compensation strategy and the stage tracking capability are also given. From these results, it can be seen that both the maximum positioning errors for X- and Y- directions are reduced from about ±50 nm to about ±10 nm by use of the SMO-based compensation of the new controller. Similarly, the rotation error in θ_z-direction is reduced to be about ±0.01 arcsec by the new controller, which is much smaller than that by the conventional method (about ±0.04 arcsec). Finally, conclusions are drawn in the last section of Chapter 3.

In Chapter 4, we have presented dynamic modelling, SMO-based controller design, and experimental verification for the Sawyer motor-based two-axis planar motion stage for precision positioning. It is found that a linear function between the generated thrust force and the motor current(s) can be obtained by synchronously changing the equilibrium position of the motor during micro-stepping drive. Based on this point, a dynamic model of the stage has been constructed. Cogging force is a reluctance force that appears from the interaction between the mover and the teeth of the platen due to the presence of permanent magnetic, and becomes the main issue during low-speed smooth operation of the stage because this mechanical vibration can be filtered out by the mechanical system itself at high-speed operation. The cogging force of the Sawyer motor is regarded as some type disturbance in this chapter. A state-space SMO has been designed for the stage by invoking a discontinuous switch control to induce the sliding motion so that the plant can be insensitive and robustness with respect to the cogging force. An estimator function has been dedicated to deal with the output errors of the SMO so that the cogging force can be precisely estimated, and compensated dynamically in the inner-loop. The developed SMO has been added to the PID controllers of X- and Y-directions, respectively and this compounded robust control structure has been implemented on DSP for the planar motion stage. Results of the experiment have indicated that the dynamic compensation strategy for suppressing the cogging force is effective. The experimental results also confirmed that by the implemented control scheme, satisfied transient performance has been obtained and the tracking error for X- and Y- motions can be noticeably achieved to about 25 nm and 60 nm, respectively.

Chapter 5 focuses on the position-sensorless issue for the Sawyer motor-based planar motion stage. D-Q modeling and linearization of the Sawyer motor have been performed to obtain a completely linear and observable model. The principle of position and speed estimation based on the SMO has been investigated. For multi-DOF planar motion stage, there are some disadvantages if position-sensorless control is adapted to all-axis of the stage: start-up problem; unwanted rotational motion; low positioning accuracy of total system, etc. In this chapter, we construct a hybrid sensorless control (HSC) for Sawyer motor-based planar motion stage. One-axis laser interferometer has been utilized to measure one translational motion and rotational motion, and then to construct feedback control for these two motions. Meanwhile, another translational motion construct closed loop control based on estimated position. For the position estimation, a SMO-based position-sensorless scheme has been implemented. Corresponding to HSC, the Sawyer motor-based planar motion stage using FSC means that two translational motions (X- and Y- motions) construct feedback control based on the position estimations for X-direction and Y-direction, respectively. And we investigate the positioning performance between the HSC and the full sensorless control (FSC) by experiment. Experimental results have shown that by the HSC the planar motion stage has the ability of sub-micro positioning accuracy (about 250 nm) in single direction compared with the positioning accuracy (about 2 μm) by the FSC and the one (about 100 nm) by the general closed-loop while using a multi-axis laser interferometer. It is confirmed that HSC is an available way to enlarge travel range and reduce the cost for position-sensing while without so much sacrifice on the positioning accuracy for this multi-DOF planar motion stage.

In Chapter 6, conclusions of the thesis and future work about the precision control of planar motion stages are given.

論文審査結果の要旨

複数のリニアモータあるいはステッピングモータを平面状に配置して，一段構造で軽量な移動部を動かす平面ステージは，多自由度かつ高速な駆動が可能な機構である。本論文はこれらの利点を持つ平面ステージに高い位置決め精度および良好な外乱抑制性能を持たせるためのアドバンスト制御理論に基づく新しいコントローラに関する研究をまとめたものであり，全編6章からなる。

第1章は緒論であり，本研究の背景，目的および構成を述べている。

第2章では，リニアモータをベースとするサーフェスモータ平面ステージにおける各自由度の干渉誤差の除去について述べている。まずステージの個々の要素を数理モデルで表現し，システム同定を行っている。次に，サーフェスモータ平面ステージの自由度に合わせて，多変数入出力を考えた非干渉要素を導入し，最適な非干渉コントローラを構築している。駆動実験の結果より，非干渉コントローラは平面ステージの各自由度間の干渉誤差を除去し，平面ステージの位置決め性能を大きく向上したことを示している。これは多自由度平面ステージの精度向上にとって重要な成果である。

第3章では，サーフェスモータ平面ステージに対して，外乱やシステムパラメータの不確かさの影響を補償することについて述べている。振動や荷重の変化など平面ステージに与える外乱を制御ループ内推定し，その影響を消す機能を持つ補償法として，スライディングモードオブザーバを導入するための外乱推定器を提案している。この方法は，精密な同定が困難な平面ステージの多自由度システムパラメータの不確かさも補償することができる。駆動実験の結果より，$XY\theta_z$3自由度の位置制御が可能であり，10 nmの超精密位置決め精度で，平面ステージの多自由度安定駆動が可能であることを示している。これはスライディングモードオブザーバを多自由度平面ステージの超精密制御に適用した初めての試みで，多自由度超精密位置決めシステムの実現にとって有効かつ非常に重要な成果である。

第4章では，ステッピングモータをベースとするSawyerモータ型平面ステージにおけるコギングフォースの抑制について述べている。マクロステッピング駆動に基づくシステムモデリングを検討し，スライディングモードオブザーバを適用するための外乱推定器を提案している。構築したコントローラはSawyerモータ型平面ステージの推力の脈動を2 Nから0.3 N以下に低減し，ステージの位置決め精度を0.1 μmまで向上させている。この結果は，超高速なSawyerモータ型平面ステージが，サブミクロンレベルの精密位置決めを実現可能なことを示す重要な成果である。

第5章では，Sawyerモータ型平面ステージに対して，高価な位置センサの代わりに，モータ駆動電流を利用してステージ位置情報を推定するという位置センサレス制御について述べている。従来の位置センサレス制御法では位置決め精度が不足する問題に対して，レーザ干渉計でY軸とθ_z軸の位置を測定しながら，スライディングモードオブザーバでX軸の位置センサレス制御を行うというハイブリッドセンサレス制御法を提案している。駆動実験により，大きい移動範囲で安定したサブミクロンレベルの位置決めが可能であることを明らかにしている。これはSawyerモータ型平面ステージの精密位置決め分野における実用化にとって有益な成果である。

第6章は結論である。

以上を要するに，本論文は平面ステージの精密・超精密位置決め制御のために，アドバンスト制御理論に基づく新しいコントローラを構築し，その実現可能性を明らかにすることで，精密工業で多用される位置決めシステムに新しいコンセプトを与えたものであり，ナノメカニクスおよび精密工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。