論文の内容の要旨

論文題目　Servo Performance Enhancement of Motion Systems via Quantization Noise Suppression and Model-Based Friction Compensation

(量子化ノイズの抑圧とモデルベース摩擦補償を用いたモーションシステムのサーボ性能の改善)

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Mechatronic systems, such as industrial robots, NC machine tools and exposure systems, often require high-performance motion control to improve the productivity and product quality. As the advancement in industry fields such as information technologies, biotechnology, electro-optics, automotive and aerospace where the required control accuracy is nanometer order or sub-nanometer order, high-speed and high-precision control systems are increasingly demanded. However, nonlinearities, such as the quantization in I/O signals and friction in mechanical components, play a vital role in control performance degradation, such as the limit cycle oscillations, torque ripples and so on. To perfectly suppress the negative effects of these nonlinearities has attracted a great deal of attention both from the theory and real applications. In this dissertation, several easy-to-use novel solutions are provided to reduce these effects for enhancing the control performance.

The main work of this dissertation is divided into two parts. In first part, output reconstruction method based on convex optimization and dithering techniques combined with Kalman filter for suppressing the effects of quantization noise, and model-based friction compensation methods for cancelling spring-like nonlinear friction in zero-speed regions are proposed from the theoretical perspective. In second part, on the other hand, the applications of the proposed methods on real systems are studied via simulations and experiments from the practical perspective.

A brief overview of this dissertation is given as follows:

In Chapter 1, configuration of high-precision motion control is introduced as the first step, and the importance of research on quantization noise suppression and friction compensation is unveiled. Following that, previous research on quantization noise suppression and nonlinear friction compensation is introduced. For reducing the quantization noise, model-based estimation techniques and curve fitting approaches are commonly employed to reconstruct the output signals. However, owe to the facts that the model uncertainties are unavoidable and the quantization noise behaves as a highly colored noise, the output reconstruction error cannot be guaranteed to converge to zero, or even be bounded. For suppressing nonlinear friction, friction compensation based on some precise model formulated by complex mathematical equations, and/or based on disturbance observer techniques are generally applied. However, the compensation strategies only consider the nonlinear friction in reverse motions, and the case of non-reverse motions (the motion direction in the acceleration is as same as the one in the deceleration in zero-speed region) were rarely taken into account. Besides, owe to the delay of low-pass filter and inaccurate velocity signals, the disturbance observer techniques cannot perfectly reduce the rapidly changed friction in zero-speed regions. In the chapter, the motivation, outline and organization of this dissertation are offered.

In Chapter 2, an output reconstruction method utilizing both observer techniques and curve fitting approaches is proposed for quantized systems to reduce the effects of quantization noise. By fitting the quantized measurements with polynomials in a moving horizon manner, a smooth signal is reconstructed via solving a convex optimization problem with some model-based constraint conditions.

According to the proposed method, the degree of the polynomials can be automatically determined and the reconstruction error can be guaranteed to be within the quantization step. In addition, the disturbance of the systems, such as the friction, can also be estimated. The convex optimization problem is a simple quadratic programming problem so that it can be solved very efficiently and accurately.

Because of the low-pass filtering characteristic of the polynomial fitting method, the phase lag introduced by the output reconstruction method proposed in Chapter 2 may not be available in high bandwidth feedback control. In addition, the quantization noise which behaves as a highly colored noise is not conquered explicitly. In order to handle the problems, the combination of dithering techniques and Kalman filter is proposed in Chapter 3. In this study, firstly, two dithered systems including the subtractively dithered system and nonsubtractively dithered system are designed to whiten the quantization noise. In the design, optimal dither signals (`optimal dither', evaluated from the perspective of probability, is the dither that can minimize the level of total measurement noise) can be obtained by taken into account of the probability characteristics of the sensing noise. Then, Kalman filter is designed to estimate the real output signals from the dithered measurements. Since the variance of the total measurement noise is theoretically calculable according to the proposed dithering methods, Kalman gain can be designed analytically.

Chapter 4 focuses on friction model and nonlinear friction compensation in zero-speed region for a high-precision two-inertia system. In many mechatronic systems, servo performance is significantly degraded in low-speed area especially in zero-speed region owe to the inaccurate velocity measurement (caused by quantization noise), the limited bandwidth of feedback control, and the insufficient friction compensation. Feedforward model-based friction compensation provides an effective solution to the problems. In this chapter, firstly, the elastic deformation dynamics of a ball-screw-driven system is analyzed. It is clarified that the mechanical deformation characteristics differ from each other according to the zero-speed crossing conditions, and therefore friction compensation should take the motion conditions into account. Based on this observation, a sinc-function-based friction compensation method for slow motions in zero-speed region including the non-reverse motions, and a

Sigmoid-function-based friction compensation method for fast reverse motions are proposed. Thanks to the very few parameters of the models, the proposed methods can save much trouble in design and maintenance, and are particularly suitable for control purposes.

In chapters 5～7, the applications of the proposed methods in chapters 2～4 on the practical motion systems are studied. Simulations and experiments are performed to show their outstanding effectiveness on improving the control performance. In chapter 5, an ultra-precision linear stage is used for verifying the effectiveness of output reconstruction method. In addition, the extension of the method for velocity estimation is also demonstrated using a DC motor. In chapter 6, the combination of dithering techniques and Kalman filter proposed in chapter 3 is applied for the ultra-precision linear stage to overcome the current quantization effects caused by Analog-to-digital converters. Besides, an extension of the method on choosing the optimal resolution of Analog-to-digital converter for a given current sensor is discussed. And in chapter 7, the friction model and friction compensation methods proposed in chapter 4 are applied to a machine tool to shown their effectiveness on enhancing the servo performance in zero-speed region.

The conclusion is given in Chapter 8. Owing to the rapidly development in industry fields such as information technologies, biotechnology, electro-optics, automotive and aerospace, low-cost high-precision motion systems will be increasingly demanded for improving the productivity and product quality. Therefore, authors believe that the proposed methods in this dissertation will attract increasing attention not only for their theoretical novelty but also for the easy-to-use properties.