Scanning Probe-Based High Accuracy On-Machine Surface Profiling Techniques

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論文内容要約

There are increasing demands for large optical components that have a feature of multiscaleness, which means that microstructures are created all over a surface of large free-form components. For example, a diffraction lens for a space telescope have larger diameter than 1 m, while micrometric grating pattern is machined all over the surface. It is, however, difficult to machine the large optical components with a high machining accuracy close to that of the workpiece with centimetric diameter because the motion error of the linear slides and the wear of the tool have significant influence on the machining accuracy in the machining of the large workpieces. Feedback machining techniques, which are re-machining techniques based on the on-machine surface profile measurement, are powerful solution to improve the machining accuracy. Optical interferometric profilers represented by the Fizeau interferometer have conventionally been utilized in the on-machine surface profile measurement of the large optical components. The interferometers, however, have drawbacks of the difficulty in free-form measurements, the extremely expensiveness, the low lateral resolution. As an alternative surface profiler, scanning probe-based surface profilers are expected to be suitable for the one-machine measurement of the large optical components. The scanning probe-based profilers have ability to obtain surface topographies of free form surfaces. And the lateral resolution is restricted not by the diffractive limit of light but by the positioning resolution of the linear slide and the tip radius of the probe. Most importantly, only an attachment probe is required in construction of the scanning probe-based on-machine surface profiler because the scanning mechanism for the probe can be substituted by the linear slides. Many research groups and companies have developed attachment probes for the processing machine, realizing high cost efficiency. The conventional scanning probe-based on-machine surface profilers, however, have problems related to each the accuracy, the lateral resolution and the vertical resolution. As for the accuracy, the conventional on-machine profilers have much lower profile measurement accuracy than that expected from the performances of the linear slides because of mainly two reasons: (1) the mismatch (Abbe offset) between the moving axis of the probe tip and the measuring axis of the displacement sensor of the slide, (2) the misalignment between the profile measurement axis and the machining axis. And as for the lateral resolution, there has been no on-machine surface profiler for the microstructures because the conventional SPM (scanning probe microscopy/microscope) techniques, which are necessary in the measurement of sub-micrometric structure, don’t have enough robustness against each the electromagnetic noise and the mechanical vibrations in the on-machine environment. Moreover, the scanning probe-based profilers have a theoretical limitation that the highest

possible measurement resolution is determined by the resolution of the displacement sensor in the scanning mechanism. In order to realize the on-machine profile measurement of future optical components represented by extreme-ultraviolet mirror, algorithms to enhance the resolution of the displacement measurement are demanded.

This thesis reports the research to establish fundamental techniques to solve the problems related to each the accuracy, the lateral resolution and the vertical resolution of the scanning probe-based on-machine surface profilers. This thesis consists of 6 chapters, beginning with chapter 1 that introduces the research background as above. The details of the contents of the subsequent chapters are as follows.

Chapter 2 proposes a mechanism and methods to realize accurate on-machine scanning probe-based surface profile measurement. The conventional commercial on-machine profilers are constructed by attaching a touch trigger probe on the processing machine. This attachment-probe concept realizes high cost efficiency. It induces, however, geometric factors of abbe offset and misalignment, which degrade the measurement accuracy. (1) Abbe offset: The scanning-probe based profiler obtains the position of the probe as the surface profile. The distance between the probe and displacement measurement axis is called Abbe offset. If the moving arm of the machine doesn't rotate, Z-directional position of the probe tip is accurately obtained by the Z-displacement sensor. However, the actual arm has error motion in yawing axis. The actual position of the probe doesn't agree with the output of the displacement sensor in the linear slide. The disagreement is called Abbe error and is a significant error factor in the attachment probe-type on-machine surface profilers. (2) Misalignment: Because the probe tip and tool tip are not at exactly the same position, there are mismatch between the measurement axis and machining axis. Therefore, these axes have to be aligned accurately. Otherwise the profile can't be evaluated. In this chapter 2, an accurate scanning probe-based on-machine surface profiler is developed. The system is constructed by attaching a long-stroke length gauge on a rotary grinder, which is utilized in the machining of large optical components. The length gauge consists of a contact probe, a linear actuator and a linear encoder. These three components are aligned coaxially to reduce the Abbe error which is one of significant error factors in conventional on-machine profilers. Position and angular misalignments between the measurement axis of the length gauge and the machining axis of the grinder also induce significant errors to the profile measurement. Accurate alignment procedures are thus established. Owing to the Abbe offset-less design and the alignment techniques, the extended uncertainty ($k = 2$) of the profile measurement is estimated to be 0.642 μm, which is reaching the limit predicted by the specification of the length gauge. The developed system successfully achieves the profile measurement of a large mirror whose diameter is 800 mm, and reveals the machining error of approximately 80 μm. After the feedback grindings based on the profile measurement, the machining error has been reduced to less than 4 μm.

In chapter 3, an ultra-precision Z scanner, which corresponds to the length gauge in chapter 2, is developed in order to realize the on-machine surface profiler for the microstructures. The Z scanner is constructed by combining a long stroke PZT actuator for servo control of the tip in the Z direction and a precision linear encoder for measurement of the displacement of the Z scanner. Capacitive or interferometric displacement sensors are conventionally adopted, but have low robustness to the electromagnetic noise and temperature fluctuation. The linear encoder, on the other hand, has high robustness to the disturbances, which is an essential advantage in applying the SPM to on-machine environments. The mounting position of the probe tip, the moving axis of the Z scanner and the measurement axis of the linear encoder were aligned coaxially in order to reduce the Abbe error. The linear encoder provides a measurement resolution of 0.5 nm over a 70 μm stroke of the PZT actuator. And owing to the Abbe offset-less design, the nonlinearity of the displacement measurement of the probe tip is smaller than 5 nmPV over an effective measurement range of 50 μm. As a demonstration, a precision PZT-driven X scanning stage has been employed for construction of an STM/AFM system in combination with the Z scanner. Profile measurements of a grating micro-structure with a small amplitude of approximately 200 nm and a prism structure with a large amplitude of approximately 25 μm are carried out using the STM/AFM system. The developed Z scanner showed promising performance in a measuring the micro-structured surfaces. From the experiment, it was confirmed that the noncontact SPM has higher ability in measurement of microstructures than the contact SPM because the noncontact SPM can utilize sharp and long tip. The ultra-precision Z scanner with noncontact SPM are thus considered to have high potential in profile measurement of the microstructures.

The linear encoder brings the robustness to electromagnetic noise. However, it is still difficult to apply the noncontact SPM to on-machine environment because of the lack of the robustness to the mechanical vibration. In chapter 4, an alternative noncontact SPM which is robust to the mechanical vibration is thus proposed. The proposed SPM is based on an electrostatic force microscope (EFM). Electrostatic force is much stronger tip-sample interaction than the interactions conventional SPMs have utilized. The EFM is, therefore, able to scan the surface in noncontact condition with the tip-sample distance of larger than 100 nm, which is more than ten times larger than that of conventional SPMs. The large tip-sample distance brings high robustness to the mechanical vibration, which is necessary in applying the SPM to on-machine environment. The EFM, however, have not been utilized for profile measurement because the electric field distribution on the sample surface may fluctuate the tip-sample distance during the scanning. Therefore, a novel calculation algorithm of the tip-sample distance is proposed in order to accurately obtain surface profile. In the proposed algorithm, the frequency shifts at two different tip height positions along the Z direction measured by a phase locked loop, and the distance between the two tip heights measured by the linear encoder, are utilized to accurately calculate the tip-sample distance cancelling the influence of the electric field distribution on the sample surface. A prototype EFM system is designed, built and employed for noncontact measurement of surface profiles of a gold-coated grating and a glass plate. It is demonstrated that the EFM can obtain nanometric surface profile image of the grating with maintaining the tip-sample distance larger than 100 nm, which brings high robustness to the mechanical vibration. Chapters 3 and 4 address the establishment of fundamental techniques for on-machine surface profile measurement of microstructures. The ultra-precision Z-scanner brings the robustness to the electromagnetic noise, and the EFM algorithm realizes large and safe tip-sample distance which significantly improves the robustness to the mechanical vibration. The combination of the ultra-precision Z scanner and the EFM algorithm would therefore be expected to be applicable to the on-machine profile measurement of the microstructures.

Chapter 5 proposes techniques for solving the problem related to the measurement resolution. The highest possible measurement resolution (minimum space period of data acquisition) of the scanning probe-based surface profiler is limited by the displacement measurement resolution. The highest possible measurement resolution of the linear encoder is approximately 1 nm because of the diffractive limit. The ultra-precision Z scanner developed in chapter 2 showed the high measurement resolution of 0.5 nm, reaching the capacity limitation of the scanning probe-based surface profiler. However, some future optical components represented by extreme ultraviolet lithography mirrors require sub-nanometric surface roughness. The proposed scanning-probe based profiler may thus not be able to satisfy the requirements from the future optical components. The resolution of the displacement sensor is determined by some factors such as the pitch length of the encoder scale, the least significant bit (LSB) of digital data acquisition system and so on. The output of the displacement sensor is thus quantized and discontinuous. And the difference between the actual value and the quantized sensor output is called quantization error (QE). One of simple solutions to improve the resolution is a low-pass filter. By filtering the QE of the displacement sensor of the scanner, smooth topography would be obtained. However, the low-pass filter is not appropriate for filtering the QE because of the difficulty in frequency designing. In particular, when the velocity of the scanner is low, the frequency of the QE is also low because the LSB of the sensor seldom changes. In order to filter such low frequency component, the cut-off frequency of the low-pass filter is required to be designed low, resulting in the scarification of the bandwidth of the measurement system. Chapter 5 proposes a novel computational algorithm to enhance the resolution of displacement sensor, including linear encoders, for the scanning mechanisms. The proposed algorithm is based on observers. And the resolution margin block, which eliminates the influence of the quantization error of the displacement sensor, is developed and integrated in the observer-based algorithm. The algorithm is able to estimate the continuous position from a quantized discontinuous output of a displacement sensor, regardless of the frequency of the QE noise. The simulation model of dynamic system which employs a linear encoder (resolution: 1 nm) as an example of a quantized displacement sensor is prepared to demonstrate the proposed algorithms. Through the simulations, it is verified that the proposed algorithm with the resolution margin block can estimate the displacement of the scanner with the accuracy of 60 pmPV. Moreover, the uncertain parameters such as friction and external force, which are required in designing the observer, are automatically estimated with the disturbance observer-based logic. In addition, the guideline to apply the algorithm to nonlinear systems as well as to linear systems is described.

The individual chapters above address to solve the problems related to each the accuracy, the lateral resolution and the vertical resolution. The developed techniques would contribute to the realization of multiscale on-machine evaluation systems for the machining accuracy of the large optical components.