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論 文 内 容 要 旨

1. Introduction

Surface Profiles of large specimens are usually measured by the scanning method. In this method, the measurement accuracy is largely affected by datum errors of the scanning stages, external vibrations and other disturbances. In order to improve measurement accuracy of the scanning method, numerous differential multipoint methods have been developed by which the information about the measured surface and the scanning error of the datum are measured by more than two sensors and the datum errors are canceled by the differential calculation of the sensors outputs. With these methods, true profiles can be obtained without using any external precision hardware reference.

The first purpose of this dissertation is to develop measurement systems to realize the generalized 2-point method and 3-point method. For this purpose, a differential interferometer and an optical probe for three point method are developed and their basic characteristics are evaluated by experiment.

The 2nd purpose of this dissertation is to extend the software datum in 1-D surface profile measurement to the situation of 2-D profile measurement, to clarify the basic characteristics of the software datum such as the spatial frequency and longitudinal resolution, to evaluate the measurement errors of the 2-D software datum. After detailed analysis of the characteristics of the 2-D software datum, the asymmetric 2-D mixed method (A2DMM) will be proposed to cancel datum errors and improve spatial frequency resolution of the 2-D scanning method.

As the 3rd purpose of this dissertation, a measuring head composed of two fiber interferometer displacement sensors and two autocollimation angular sensors for realizing the 2-D asymmetric mixed method is developed and the viability of this method will be demonstrated by experiment.

The 4th purpose of this dissertation is to develop calibration method to calibrate the developed sensors. A new self-calibration method for calibrating interferometers having nanometer accuracy is proposed, and the basic characteristics of the method are discussed. The developed displacrment sensors are calibrated by the proposed self-calibration method.

2. Surface Profile Measurement Using Differential Interferometer

In this chapter, a compact phase modulated differential interforometer using a laser diode as the light source is described to realize the generalized 2-point method. Two kinds of data processing methods for the interferometer are proposed and discussed. The basic characteristics of the measurement system using these two signal processing methods are evaluated and compared. The developed interferometer is used to measure surface profiles of a block of optical flat.

The results of this chapter are summarized as follows ;

1) A phase modulated fringe-counting method for processing interference signals is proposed, in which the conventional fringe-counting and phase modulation methods are combined in order to extend the measurement range and improve the resolution of the interferometer.
2) A simple phase modulated time-counting method for interference signal processing is proposed, in which the measured displacement can be obtained by detecting the zero point and measuring the time interval between two adjoining zero points of only one interference signal.
3) A compact phase modulated differential interferometer using a laser diode as the light source is described, and the viability of the proposed signal processing mothods are verified by experiments using this interferometer.
4) The basic characteristics of the interferometer, when the proposed two methods are used for phase detection, are evaluated and compared. The interpolation errors of the modulation PZT is calibrated to be about 10nm when each of the methods is used. The stability of the interferometer, when the phase modulated fringe-counting method is used, is higher than that when the time-counting method is used.
5) The developed differential interferometer is used to measure sectional surface profile of an optical flat with maximum repeatability error of 14.6 nm in a measurement lengh of 100 mm.

3. Self-calibration of Displacement Sensors

In this chapter, a self-calibration method for calibrating linearity error of the developed sensors is proposed. The principle and the basic characteristics of this method is analyzed and calibration error is discussed in detail. The developed displacement sensors are calibrated by the proposed method and the results are compared with that calibrated by using a capacitance displacement sensor as its reference.

The results of this chapter are as follows :

1) Analysis shows that the calibration accuracy of the proposed self-calibration method can approach the limit of interferometer resolution as determined by the SNR and the stability of the measurement system without using any precision reference.
2) The influence of various sources of errors, such as the error of the assumed displacement ratio, random errors, and drift of the measurement system, was discussed in detail. Random errors and drift do not affect the tendency towards convergence, and the error of the displacement ratio can be corrected automatically during the calibration process.
3) Analysis shows that the proposed self-calibration method can also be used to calibrate interferometers having a single sensing beam. The calibration setup is relatively simple to construct and compact in size, enabling on-machine calibration.
4) The developed interferometer was calibrated by the proposed self-calibration method. The linearity error due to the modulation element could be fitted to parabolic curves. The height of the parabolic curve was estimated to be approximately 9.6 nm, with an average maximum repeatablity error of approximately 0.54 nm, where as the standard deviation was estimated to be less than 0.1 nm.
5) The developed interferometer was also calibrated by the conventional comparison method using a capacitance

displacement sensor as the reference. Experiments show that the conventional comparison method introduces the linearity error of the reference sensor into the calibration results. When the linearity error of the capacitance sensor is removed, the calibration results of the two methods coincide, with an average height difference of about 0.1 nm.

6) Each period of the calibrated linearity error can be fitted by a parabolic curve, with an RMS error less than 0.6 nm. These curves can be taken as the interpolation curve of the modulation PZT. Results obtained by averaging the data of four measurements yielded a standard deviation of 0.1 nm.

7) The ability of the method to compensate for measurement errors was evaluated for several measurement examples. For single measurements, the maximum error and RMS error from the calibrated curve can exceed 1.56 nm and 0.88 nm, respectively. If the data from several measurements are averaged, the maximum error and RMS error decreases to less than 0.63 nm and 0.33 nm, respectively.

4. Surface Profile Measurement by 3-point Method

In this chapter, a new laser beam-vibration displacement detection method was proposed and the principle of the method was discussed in detail. The error caused by the inclination of the measured surface was considered and an inclination error compensation method was proposed. An optical probe composed of three displacement sensors based on the proposed laser beam-vibration displacement detection method was developed to realize the generalized 3-point method for machined surface profile measurements.

The conclusions of this chapter are summarized as follows :

1) According to the proposed method, the measured displacement can be linearly converted to time intervals between two zero cross points of the bi-cell photo diode output in one perid of the modulation voltage by modulating the incident laser beam and obtained by measuring these time intervals.

2) Analysis and experiment show that the error caused by the inclination of the measured surface can be compensated by using a quadruple photo diode to detect time intervals between three zero cross points.

3) Analysis and experiments show that sensors based on this principle are insensitive to the instability of the reflectivity of the measured surface and the fluctuations in the intensity of the light source which made it possible to be used for on-machine measurement of machined surfaces.

4) The developed sensors are calibrated with a maximum repeatability error of approximately 0.1 μm by using a capacitance displacement sensor as their reference. The stability of the measurement system is evaluated to be 0.1 μm during one hour period of time.

5) The sectional surface profile of an aluminum plate is measured with a repeatability of 0.32 μm by using the generalized 3-point method with the developed optical probe under conditions simulating on-machine measurements.

5. Basic Study on the Measurement of 2-D Surface Profiles

(Part 1 : Transfer Function and Resolution)

In this chapter, the theory of 1-D software datum is extended to two dimensions. The basic characteristics of 2-D software datum for 2-D profile measurement are considered in detail.

The conclusions of this chapter are summarized as follows

1) Four sensors (displacement sensor or angular sensor) are needed to construct a 2-D software datum by which the datum errors of the scanning stage can be removed. Among the possible differential methods, four typical arrangements are presented and discussed.

2) The spatial frequency resolution is limited by the zero point of the transfer function of the method and the number of zero points of the transfer function can be reduced by asymmetric arrangement of the sensors.

3) The longitudinal resolution is determined from the resolution of each sensor and the zero point of the transfer function. It also varies with the arrangement of the sensors if the displacement sensor and angular sensor are used at the same time.

4) With respect to spatial and longitudinal resolutions, the asymmetric 2-D mixed method is superior to the others.

6. Basic study on the measurement of 2-D surface profiles

(Part 2 : Measurement Error Analysis)

In this chapter, the measurement errors of the 2-D differential methods presented in chapter 5 are evaluated by analyzing the characteristics of the transfer function and differential output of the software datum.

The conclusions are as follows :

1) The errors of the sensors affect the measurement results in the following aspects : the expectation of the error causes the zero adjustment error, whereas the variance of the error detemines the SNR of the method. The self-correction method used in 1-D surface profile measurement can be extended to 2-D profile measurement.

2) The positioning error of the measuring head during scanning has a close relation with the spatial frequency of the measured surface.

3) The error caused by the drift of the temperature may by amplified by the transfer function at the zero point of the transfer function.

4) The probe distance error affects the measurement results by introducing error to the transfer function, and this error is amplified by the transfer function at the zero point.

7. Basic Study on the Measurement of 2-D Surface Profiles

(Part 3 : Equipment Development and Profile Measurement)

In this chapter, a 2-D surface profile measurement apparatus for realizing the asymmetric 2-D mixed method was developed, and the apparatus is used to measure 2-D surface profiles of an optical flat.

The conclusions can be summarized as follows :

1) Two displacement sensors and two angular sensors were used to construct a high spatial frequency and longitudinal resolution 2-D software datum, called the asymmetric 2-D mixed method, in which 2-D datum errors are canceled.

2) Based on the principle of the method discussed in chapter 5, two phase modulated fiber interferometric displacement sensors and two angular sensors based on the principle of the autocollimator are developed and used to construct the measuring probe.

3) The basic characteristics of the fiber displacement sensors were evaluated. The 20-minute period stability of the sensors were evaluated to be about 13.6 nm and 14.5 nm, respectively. When calibrated by the self-calibration method, the displacement sensor showed a linearity error of about 14 nm and a resolution of 2 nm.

4) The basic characteristics of the angular sensors were evaluated. The stability of the sensor over a 20-minute period was about 0.1 arcsec. When calibrated using a lever system driven by a calibrated piezo actuator and Nikon autocollimator, the angular sensor showed a linearity error of about 2 arcsec and a resolution of 0.02 arcsec.

5) The developed apparatus was used to measure the 2-D surface profile of a 128×64 mm^2 silver-coated glass-plane mirror. Repeatability was approximately ± 20 nm. The reliability of the measurement was verified by comparing the results of two measurements in which the sample was turned by 90°.

6) Sectional surface profiles obtained by A2DMM were selected and compared with those obtained by 1-D differential laser interferometer DLI method and 1-D differential laser autocollimation DLA method. Investigations

demonstrated good agreements between the measurement results obtained by different methods.

7) Furthermore, the measurement results are compared with that measured using Zygo interferometer, and the results are basically agreed.

8. Conclusions

In this chapter, the conclusions and results of this dissertation are summarized.

審 査 結 果 の 要 旨

超精密加工の分野で要求の高まっている大型非球面鏡のオンマシン形状測定の実現のためには，機械の有する２次元の走査案内よりも高い精度の測定基準を機上に構築する手段が不可欠になる。本論文は，複数のセンサの差動出力の演算による２次元走査を中心とした種々の測定基準（ソフトウェアデータム）の構築法を体系的に比較検討し，分解能と安定性を定量的に明らかにするとともに，新しい２次元ソフトウェアデタムの構築法を提案し，２次元走査における絶対測定を実現した結果を述べたもので，全編８章からなる。

第１章は緒論で，本研究の背景と目的を述べている。

第２章では，オンマシン状態での使用が可能な小型の差動干渉変位計を試作し，それを用いた２点法による真直度測定を試みたもので，後の２次元ソフトウェアデータムによる測定結果の比較データを与えている。

第３章では，高精度の変位，形状を議論するとき不可欠となるナノメートルオーダの変位の自律校正法を述べている。この章で提案した差動干渉変位計の自律絶対校正法により，変位計測精度が初めてサブナノメートルの信頼度で絶対的に保証できることになり，以下の章の高精度形状測定の基礎を与えている。

第４章では，変位計３本を不等間隔に並べて行う真直度測定のための一般３点法を実現する光学式プローフを試作し，その方法の有効性を初めて実験によって確認している。これも，後の２次元ソフトウェアデータムの一つの基礎を与えている。

第５章では，２次元走査のためのソフトウェアデータムの構築法を検討したもので，変位計を角度計の配置の仕方による形状成分伝達関数の違いを理論的解析と数値計算から明らかにし，最良のデータムの構築法を示している。これは精密工学上高く評価される。

第６章では，複数のプローブ間に生じるゼロ点誤差の新しい決定法を述べている。２次元走査方式での形状の絶対測定を初めて可能にしたことは，精密工学上高く評価できる。

第７章では，上の第５，６章で理論的に得られた成果をもとに，２次元混合法プローブを試作し，平面形状の計測実験を行った結果で，条件を種々に変えての繰返し測定の再現精度から極めて信頼性の高い絶対測定ができることを示している。この結果は，実用上の貴重な成果である。

第８章は結論である。

以上要するに，本論文は大型の多様な超精密鏡面形状を１次元的，２次元的に走査測定するために不可欠なソフトウェアデータムに関して，最適のプローブの設計指針を与え，また，開発したプローブの自律校正の手法を示すなど多くの重要な成果を得ており，精密工学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。