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（レーザオートコリメーション法に基づく高感度角度センサに関する研究）
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論文内容要旨

This thesis presents highly sensitive, fast response speed and compact multi-axis angle sensors based on laser autocollimation method.

In industrial activities such as manufacturing and inspection, physical quantities like angle and length are benchmark parameters for keeping and improving the quality of products. Nowadays, precision machines such as the machine tool for producing precision optical elements and the coordinate measuring machine (CMM) for evaluating products in machine shops are widely used. Many of such machines have precision linear stages as key components, which normally have motion errors around the axis of movement direction of stages. The measurement of stage movement errors is essential in evaluating the performance of these machines.

Stage motion errors are usually expressed as a position error with respect to the moving direction of the carriage of the stage, and a translational motion (straightness) error that is vertical to the moving direction. The former error can be measured by using a laser interferometer or a linear encoder, while the latter error is usually measured based on a straightedge. Additionally, three-axis angular motion errors (roll angle $\Delta\theta_X$, pitch angle $\Delta\theta_Y$ and yaw angle $\Delta\theta_Z$) also exist to cause unexpected Abbe-error. Therefore, it is important to measure the posture information of the carriage of the stage for compensation of Abbe-error. The differential method by using two interferometers that are preset on the stage is used for measurement of posture angle control. However, this method requires multiple sensors and it increases the complexity of the measurement system. Moreover, these sensors must be highly sensitive with fast response speed, and must be capable of non-contact measurements so that it would not influence to the dynamic properties of the stage. On the other hand, an angle sensor can measure minute tilt angle motion of the target directly. Therefore highly performance angle sensors are required.

Angle sensors based on the principle of autocollimation, which are conventionally called autocollimators, can accurately measure small tilt angles of a light-reflecting flat surface. Autocollimators have a long history of being used in metrology laboratories for calibration of angle standards, such as polygons, rotary index tables and angle gage blocks. They are also traditionally used in machine shops for surface profile measurement of straightedges, machine tool guideways and precise surface plates as well as for measurement of static translational angular motion errors of the stages. But autocollimators cannot be used for dynamic measurements, since they use a charge-coupled device (CCD) as the photoelectric element, with frequency bandwidth on the order of tens of hertz. Furthermore, the sensitivity of a CCD for the position of a light spot is low so that a relatively large lens with a focal length of hundreds of millimeters is required to yield highly sensitive angle detections, which makes the autocollimator bulky, expensive, and difficult to integrate into other precision systems.

For these reasons, today highly performance angle sensors that have highly sensitive with fast response speed, multi-axis measurement, and must be capable of non-contact measurements, are required. A simple optical method for a simultaneous measurement of two-axis angular motion errors such as pitch angle $\Delta\theta_Y$ and yaw angle $\Delta\theta_Z$ is feasible by using laser autocollimation method with a fast response two-dimensional position-sensing detector. In this research, angle sensors based on laser autocollimation are described. To fulfill the requirement to the angle sensor, these sensors consist of a quadrant photo diode (QPD) as their position-sensing detector. This optical system allows these angle sensors to be able to reduce the dimension while maintaining highly sensitivity and fast response speed. In addition, to achieve a simultaneous three-axis angle measurement, a diffraction gird is used as a target reflector instead of a plane mirror. And reflected diffraction beams are applied for the three-axis angle measurement. The research issues that are derived from technology trends are follows:

- Highly sensitive (resolution: ±0.1 arc-seconds).
- Quick response speed (1 kHz frequency bandwidth).
- Compact size (less than 100 mm-cube).
- Multi-axis angle detection (two-axis or three-axis).

At the first stage of this thesis, general background and brief introduction for small angle detection methods are described. And typical applications of the angle sensor are overviewed. Research issues and outline of this research are also presented.

In Chapter 2, a compact but highly sensitive two-axis angle sensor based on the principle of laser autocollimation is described. The angle sensor consists of a laser diode (LD) as the light source, and a QPD as the position-sensing device. To maintain highly sensitivity without enlarging the sensor size, the relationship between the beam spot size on the focal plane of the objective lens and width of gaps (dead space) is analyzed based on geometrical optics. As a result, it is confirmed that an objective lens with a short focal length can be employed without reducing the sensitivity of the system, which facilitates miniaturization of the angle sensor. This is because the sensor only requires a small extra target mirror to be mounted on the stage. The cross-talk between two-axis angles and influence of alignment errors of the QPD (a rotational error and a mounting position error (defocus error)) are estimated by computer simulation. Then the sensitive single lens two-axis micro-angle sensor

(SMAS) is developed based on the analysis results. To reduce the dimension of the sensor, the sensor consists of a plano-convex lens for laser beam collimation and focusing. The assembly can be also simplified comparing with the conventional optical layout of the two-axis angle sensor, since displaying optical components of the LD, a PBS, a QWP, and the lens are on a single straight line. The finalized dimension of the SMAS is 15.1 mm × 22.0 mm × 14.0 mm (W × D × H). Therefore, the SMAS is small enough to be able to integrate into precision machines like a precision stage without influencing original dynamic properties of it. From the experimental result of small angle detection, the resolution of the SMAS is approximately ±0.1 arc-second in each direction. The cutoff frequency of the sensor amplifier is set to be 15 kHz.

In Chapter 3, a relationship between the sensor sensitivity and the working distance of a two-axis angle sensor based on laser autocollimation is surveyed. The working distance is defined as a distance between the angle sensor and the target reflector. At the first part of this chapter, the prototype two-axis angle sensor for evaluation of the working distance is fabricated. From evaluation results of the working distance of the prototype two-axis angle sensor, a general problem of the optical system that can be reduced the accuracy of the angle measurement is found out. This is because the sensor sensitivity changes up to 12.4 % from the representative value of average sensor sensitivity of V_{a_m} over the measurement range from 100 mm to 450 mm. Two error components that can influence the deviation of the sensor sensitivity are proposed based on geometrical analysis and Gaussian beam optics. To reduce the deviation of the sensor sensitivity less than 1 %, computer simulation is carried out to obtain optimal optical parameters for the angle sensor. Then new two-axis angle sensor is developed based on the analysis result. The new angle sensor is highly sensitive to the tilt motion of the target, but has insensitive deviation of the sensor sensitivity over the effective working distance of 500 mm. This is because the deviation of the sensor sensitivity in both angle directions confirmed to be less than 0.5 % from the experimental result. And the dimension of the angle sensor is 60.0 mm × 89.0 mm × 49.0 mm (W × D × H). Therefore it is able to facilitate a measurement of the angular motion errors (pitch angle $\Delta\theta_Y$ and yaw angle $\Delta\theta_Z$). From the signal width of the evaluation result of the noise level in short period of 5 seconds, the Type 3 angle sensor has capability of detecting the small tilt angle displacement up to ±0.007 arc-second in $\Delta\theta_Y$-direction and ±0.008 arc-second in $\Delta\theta_Z$-direction. The frequency bandwidth of the sensor amplifier is set to be 1.9 kHz. In addition, the compensation that is focused on the change of the optical spot diameter on the detector is carried out against the experimental result. And the effectiveness of the compensation is also confirmed.

In Chapter 4, an optical method and a basic optical system for measurement of three-axis angles based on the laser autocollimation has been proposed at the first part of the chapter. As in the case of a two-axis angle sensor, a three-axis angle sensor consists of a LD as the light source, and a QPD as the position-sensing device. Differing from a conventional two-axis angle sensor, the angle sensor uses a diffraction grid as the target reflector instead of a plane mirror for improving the two-axis measurement method based on laser autocollimation to the three-axis angle measurement. Then the 0^{th}-order and $\pm 1^{st}$-order diffraction laser optical spots reflected from the diffraction grid are used for realizing the simultaneous three-axis angular detection, while it has restriction of the working distance because of the usage of ±1st-order diffraction beams. Theoretical analysis and computer simulation are carried out for confirming the validity of the roll angle detection and to derive the roll angle sensor sensitivity. From analysis results, highly sensor sensitivity include in roll angle direction can be feasible by using short focal length of the objective lens just the same as the two-directional angle sensor. This result is feasible for miniaturization of the three-axis angle sensor. Then the prototype three-axis angle sensor is developed based on the analysis result. The prototype three-axis angle sensor has two parts of beam isolation unit and receiving autocollimation unit. A two-axis rectangle grid that has the grid interval of $p = 5.5$ μm in both directions is used as the target reflector for the prototype three-axis angle sensor. Then sensor output curves in each direction are measured. From the experimental result of the small angle detection and the ray-trace simulation result, it is confirmed that the roll angle sensor sensitivity is low compared with the theoretical value because of lens aberrations. The prototype thee-axis angle sensor has its resolution of better than ±0.1 arc-second in $\Delta\theta_Y$ and $\Delta\theta_Z$-directions and up to ±1 arc-second in $\Delta\theta_X$-directions from the experimental result of the small angle detection. The cutoff frequency of the sensor amplifier over the experimental measurement is set to be 3 kHz. The dimension of the angle sensor is 100 mm × 155 mm × 80.0 mm (W × D × H).

In Chapter 5, additional two types of measurement methods for the simultaneous measurement of three-axis angles are presented by using different combinations of the diffraction optical spots. These methods have an advantage of reducing a receiving autocollimation unit that consists of the objective lens and the QPD detector. From computer simulation results, each method can measure three-axis angles independently and the difference among them is small enough to be ignored. The effectiveness of these methods is also confirmed by experimental results of the Type 2 three-axis angle sensor. The Type 2 three-axis angle sensor consists of the three objective lenses for the purpose of reducing the influence of the lens aberrations. And the target reflector of the Type 2 three-axis angle sensor is a two-axis rectangle grid ($p = 5.5$ μm). It has been verified that each method can measure the three-directional angular displacements. Then a highly sensitive three-axis angle sensor is developed based on analysis results. The target of the angle sensor is a one-axis diffraction grid with its grid interval of 1.7 μm. The two reflected diffraction beams of the 0th-order and the 1st-order beams are used for the three-axis angle measurement. And the three-axis angle sensor employs the afocal system to realize the highly sensor sensitivity and compaction of the length of its optical system. The finalized dimension of the angle sensor is 86 mm × 86 mm × 47 mm (W × D × H). From the result of the small tilt angle detection, the angle sensor has capability of detecting ±0.01 arc-second in each direction. In this experiment, cutoff frequency of sensor amplifiers is set to be 1.9 kHz. The optical layout and other basic characteristics of the angle sensor are also described.

In Chapter 6, summary of the research findings and conclusions of this dissertation are discussed.

論文審査結果の要旨

近年，大面積の高精度鏡面形状計測や精密位置決め技術の向上のために，多自由度の微小角度変化を高感度，高速，非接触に計測する要求が高まっている。また，インプロセス計測やフィードバック制御などの観点から，各種装置に組み込み可能な小型角度センサの開発が求められている。本論文は，レーザオートコリメーション法を基にした最大３軸の角度検出が可能な小型かつ高感度な角度センサを具現化するための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，４分割フォトダイオード（ＱＰＤ）を受光素子に用いることで角度検出の高感度化とセンサの小型化の両立を実現した，応答性に優れたレーザオートコリメーション法ベースの角度検出原理について述べている。また，幾何光学に基づく解析やシミュレーションを通じて原理の有効性ならびにピッチング，ヨーイング方向の検出感度に影響を与える因子に関しても検討をしている。さらに，１枚のレンズでビームのコリメート並びに集光を行う小型化に適した光学系に対して，提案した原理に基づき短焦点距離の対物レンズを組み込むことでセンササイズを大幅に削減した小型２軸角度センサの開発を行い，その基本特性の評価を行っている。この結果は各種装置に組み込み可能なほど小型かつ高感度な２軸角度センサを実現した重要な成果である。

第３章では，第２章で提案した角度検出原理に基づく高感度２軸角度センサを用いてリニアステージの運動誤差計測を行う際に重要となるセンサの有効作動距離の評価と，２軸角度センサの最適設計について述べている。ステージの可動部に取り付けられた平面ミラーの移動に伴い，角度センサの検出感度が変化してしまう問題点についてその原因を考察し，幾何光学ならびにガウシアン光学に基づいた光学モデルによるシミュレーション解析を行うことで，典型的なリニアステージの可動範囲である 500 mm において感度変化の影響が１％以下となるセンサ設計値の最適値を導出した。また，求めた設計値を用いて新たに高感度２軸角度センサを開発し，有効作動距離が 500 mm であり，かつ 0.01 秒以下の角度検出が可能であることを確認した。これは提案した角度センサの応用範囲を大きく広げた成果である。

第４章では，測定ターゲットの平面ミラーを反射回折格子に変更することで，従来のレーザオートコリメーション法の利点を生かしつつ角度検出の自由度を拡張した，３軸角度の検出原理を提案している。また，本手法におけるローリング角度検出感度に関して，幾何光学を用いた解析とシミュレーションにより導出している。さらに，原理に基づきプロトタイプ３軸角度センサの開発を行い，その基本特性の評価並びに原理の有効性の確認を行っている。これらは高感度かつ高速な３軸角度センサを実現するために非常に重要な成果であり，高く評価される。

第５章では，第４章で提案した測定原理に基づいて高感度かつ小型な３軸角度センサの開発について述べている。まず小型化に適した３軸角度検出方法を提案し，その有効性についてシミュレーション並びに実機を用いて検討を行っている。また，角度検出ユニットを各反射回折光に分割することで，レンズ収差の影響を低減している。これらの手法を基に１辺が 100 mm 以下の小型かつ高感度な３軸角度センサを新たに製作し，その基本特性の評価を行い，カットオフ周波数 1.9 kHz において 0.1 秒以下の微小３軸角度検出が可能であることを確認している。これは高感度３軸角度センサの実現性と角度検出原理の有効性を示す有益な成果である。

第６章は結論である。

以上を要するに本論文は，従来のオートコリメーション法では相反する性質であった，高感度かつ小型である特性を有し，また検出が不可能であったローリング角度変位を含む最大で３軸角度が検出可能である応答性に優れたレーザオートコリメーションベースの角度検出原理を提案し，その実現可能性を明らかにしたものであり，精密位置決め分野や精密測定の分野における角度センサ適用の可能性をも拓くもので，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。