Application Principle and Development Forecast of Photoelectric Sensors in High-Precision Machining Machines

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Abstract. This paper systematically reviews the operating principles and applications of three key types of photoelectric sensors used in high-precision machining: grating scales/encoders, laser displacement sensors, and laser interferometers. It summarizes the development of their structures, measurement principles, and system integration. High-precision grating scales provide high-rigidity absolute position feedback through steel-strip substrates and single-field scanning technology; laser displacement sensors enable online high-precision detection through confocal principles and high-protection designs; and laser interferometers support dynamic diagnosis through coaxial optical paths and multi-degree-of-freedom integration. Together, these sensors form a closed-loop accuracy-assurance system for modern machine tools, covering motion-axis feedback, in-process measurement, and system-accuracy calibration. Based on this analysis, the paper discusses current challenges related to reliability under extreme operating conditions, multisource data fusion, and system cost.

Keywords: photoelectric sensor; real-time monitoring; error compensation; positioning accuracy

1 Introduction

Photoelectric sensors can attain non-contact measurement with a resolution at the nanometer level, which offers extremely precise sensing abilities to machine tools, and these sensors transform alterations in optical signals into electrical ones, having the characteristics of high detection sensitivity and being applicable over a broad scope [1], and this not only made it possible to monitor in real-time and compensate for errors like thermal deformation and vibration, but also changed machine tools from passive devices that actuate into intelligent systems possessing self-sensing and self-decision-making capabilities, and it was a crucial enabling technology for attaining machining precision below the micron level and closed-loop intelligent control.

Nowadays, the utilization of sensors in Computer-Numerical Control (CNC) machine tools has shown a trend of systematic and multi-dimensional integration and has become a crucial means of guaranteeing machining precision and elevating automation levels, diverse sensors, in line with their functional traits, are methodically employed in the monitoring of vital parameters like displacement, position, speed, pressure, and temperature of machine tools [1], among

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photoelectric sensors, high-precision grating scales/encoders, laser displacement sensors, confocal displacement sensors, and laser interferometers have been extensively applied in the area of displacement detection, high-precision grating scales were utilized for real-time feedback of linear displacement while pulse encoders were used for that of angular displacement, these helped form a fully closed-loop or semi-closed-loop control system and considerably enhanced positioning accuracy [2], grating displacement sensors had the benefits of a simple structure, high resolution, and strong resistance to electromagnetic interference so they became an important approach in the field of precise displacement measurement [3], laser triangulation displacement sensors, in contrast, had measurement accuracy at the submicron level and were appropriate for high-precision non-contact measurement situations [4].

Generally, the utilization of sensors in Computer Numerical Control (CNC) machine tools was changing from detecting a single parameter to fusing multiple sensors and intelligent diagnosis, under this trend, sensor structures were gradually getting smaller and more integrated so as to fit into the limited installation spaces inside machine tools and make high-precision non-contact measurements easier, for example, fiber-based spacing sensors which had an outer diameter of just 0.4 to 3 mm could be smoothly integrated into crucial parts of machine tools allowing for detecting shape and position errors at the nanometer level without damaging the measured surface [5], these sensors showed great potential in high-precision machining, printing machinery, aerospace and other fields thus further driving the intelligent development of machine tools by improving dynamic precision, maintaining stable operation and achieving condition monitoring and fault prediction, and the aim of this paper was to summarize the developmental trends of main stream opto-electronic sensors that were being used in high-precision machine tools available in the market at that time and provide guidance for their future development.

2 The working principle of photoelectric sensors and their role in high-precision machining machines

Currently, the mainstream photoelectric sensors used in high-precision machining machines on the market include high-precision grating scales/encoders, laser displacement sensors, and laser interferometers.

2.1 Operating principle and specific function of high-precision grating scale/encoder

High-precision grating scales / encoders serve as crucial elements in the closed-loop control systems of CNC machine tools, essentially being displacement sensors that function according to optical principles and can directly transform mechanical displacement into high-quality digital signals, with their fundamental working mechanism resting on the optical diffraction phenomenon of Moiré fringes and the photoelectric conversion process: when the main grating and the indicating grating have relative movement, the minute angle between their scale patterns leads to the formation of alternating bright and dark Moiré fringes, and the distance these fringes move is far greater than the actual displacement of the grating, thereby attaining the optical magnification of displacement, and the system primarily comprises a main grating (scale grating) and a readhead (indicating grating), where the main grating was generally attached to the movable parts of the machine tool and was an optical or metal ruler with periodic scale markings while the readhead was fixed to the stationary parts and had a light source, a small grating, and a photoelectric detection array integrated inside it, and in CNC machine tools, such sensors were extensively utilized for displacement detection, like linear gratings and pulse encoders which were separately employed for providing high-precision feedback of linear displacement and angular displacement, constituting a fully closed-loop or semi-closed-loop control system and substantially enhancing the positioning accuracy and dynamic performance of the machine tool.

When the gratings shift in relation to one another, the magnification function of Moiré fringes transforms grating pitch displacement at the micrometer level into fringe movement at the millimeter level, making it easier for a photodetector to collect subsequently and allowing for accurate displacement computation via a signal processing circuit; the measurement precision and resolution of the grating scale are basically determined by the performance of its central sensitive component, the diffraction grating; over the past few years, enhancing the microscopic geometric form of gratings to boost the efficiency and signal quality of high-order diffracted light has been a leading research approach for attaining nanometer-level precision measurement, for instance, high-order diffraction gratings with an isosceles triangular cross-sectional shape can better regulate the distribution of diffracted light fields, consequently getting purer and higher-contrast interference signals in optical encoders which offers a new technological route for overcoming the nanometer-level precision limitation of linear measurement [6]; in high-precision machine tools, high-precision grating scales / encoders mainly function to guarantee the accuracy of machining operations, realize complete closed-loop control, directly measure and compensate for all mechanical transmission inaccuracies, offer high-resolution, high-response true position feedback, strengthen servo stiffness, and thus attain repeatable and traceable machining precision, ensuring the uniformity of part dimensions while enhancing surface processing quality, enabling high-speed, high-precision machining, and shortening cycle time.

2.2 Operating principle and specific function of the laser displacement sensor

The fundamental operational mechanism of a laser displacement sensor is based on laser triangulation which basically transforms minuscule height alterations into detectable spot-position shifts on the detector, and the laser triangulation displacement sensor comprises three crucial elements namely a laser transmitter, a receiver lens (also known as an imaging lens) and a position-sensitive detector; when commencing the measurement process, the laser beam creates a tiny spot on the surface of the object to be measured and then the receiver lens gathers the diffused or specular reflection light from the object's surface and after being received, the image of the spot on the object's surface forms an image point on the position-sensitive detector; if the object to be measured moves vertically along the laser beam axis, the position of the spot on the object's surface would shift linearly correspondingly and ultimately the position-sensitive detector gauges the position of the spot center in real-time, computes the actual displacement of the object by means of triangular geometry and emits a standard signal like an analog voltage.

In high-precision machining machines, laser displacement sensors mainly serve to detect the state of tools, rapidly align and set the positions of workpieces, carry out dimension measurement, keep real-time monitoring of the workpiece surface quality as well as detect the machine's state, which guarantees processing safety, prolongs tool life, gets rid of human errors in workpiece positioning, prevents the need for secondary clamping, optimizes surface quality and improves the accuracy and stability of the machine during long-term operation.

Laser displacement sensors are not only ideal for dimensional measurement and condition surveillance inside machine tools but also show great accuracy and effectiveness in the area of industrial on-line inspection; for example, in the dimensional examination of railway wheelsets, combined laser displacement sensors could attain high-precision dynamic measurement of wheelset sizes by gathering contour characteristics of the wheel flange and tread, dealing with point cloud data, and carrying out least squares fitting; relevant research indicated that this approach had a maximum detection error of just 0.2mm and a maximum single detection time of 46s, which demonstrated the high dependability, high precision, and quick response detection abilities of laser displacement sensors in complicated industrial settings, and this further showed that laser displacement sensors had wide application potential in non-contact, high-precision, and highly flexible measurement situations.

2.3 Operating principle and specific functions of laser interferometer

The fundamental operating principle of a laser interferometer relies on the interference phenomenon of light which renders it among the crucial techniques for attaining nanometer-level precise measurement and when the optical path divergence between two coherent light beams was an integer multiple of the wavelength constructive interference (bright patterns) took place while being a half-integer multiple led to destructive interference (dark patterns) so by measuring the quantity of bright and dark alterations in the interference patterns the displacement could be precisely determined and as a central means in nanometrology laser interferometer technology together with grating interferometers and time-grating sensors made up the basic framework for contemporary ultra-precision measurement [7].

In high-precision machining machines, laser interferometers are mainly used for diagnosing geometric errors and carrying out high-precision measurements regarding diverse axis positioning inaccuracies, straightness deviations, and play; moreover, these devices are also utilized for analyzing dynamic performance and thermal errors by evaluating how errors vary during high-speed operation and when there is a temperature increase in the machine tool and what's more, they could produce compensation parameters for the numerical control system to make error compensation possible.

Laser interferometers are also of great significance in analyzing the thermal performance and maintaining the precision of machine tools and research has shown that an online monitoring system for the thermally-induced preload of spindle bearings could be built based on them which was able to monitor alterations in the bearing preload at diverse rotational speeds in real-time thus providing vital data support for the analysis of spindle thermal traits, the prediction of thermal errors, and the basis for compensation and Wen Jinlong and his team made use of a laser interferometer to accomplish real-time measurement of the thermally-induced preload of machine tool spindle bearings at various rotational speeds and the system had high reliability as the differences in simulation and experiment were no more than 5% presenting an efficient method for the thermal performance monitoring and precision control of machine tool spindles [8].

3. Case comparison

3.1 Examples of application changes of high-precision grating scales/encoders in high-precision machining tools in the past ten years

Since 2015, there have been substantial structural alterations in the realm of high-precision linear grating scales and one of the key impetus for this shift was the progress in grating manufacturing technology, especially the utilization of laser interference lithography technology which made it possible to fabricate large-area nanoscale periodic grating structures efficiently and with high precision on diverse substrates, establishing the basis for performance breakthroughs in grating scales [9].

Against this background, the emergence of metal strip grating scales has become predominant, like the Invar alloy steel strip utilized in the Heidenhain LIDA 400 series, and the key novelty resides in the employment of sophisticated micro-nano processing techniques (for instance, laser interferometric lithography) to produce diffraction grating lines having an exceptionally high linear density and uniformity on flexible metal strips with a very low thermal expansion coefficient, which fundamentally strengthens the impact resistance and installation tolerance of the product, and when installing, the steel strip just needed to be secured at both ends and the middle portion could automatically conform to the surface of the machine tool bed, simplifying the assembly and adjustment procedures significantly, getting rid of the installation stress resulting from forced fitting in traditional glass gratings and enhancing long-term stability.

At the same time, the combination of the absolute position feature and incremental measurement has become another significant technological advance; take the RGSZ/RGSL stainless-steel tape scales utilized in Renishaw's RESOLUTE series for instance, they incorporate an incremental grating track along with a pseudo-random coding track which offers absolute position data on a single scale unit via ultra-precision coating and pattern-making procedures and the creation of such intricate microstructures is also made possible by high-precision lithography techniques; this "thin-film" design is more resistant to oil marks and scrapes compared to traditional etched chrome lines and also incorporates the absolute position memory capability so that the machine tool linear axis can refrain from carrying out a "zero return" procedure after a power cut and restart, offering vital support for attaining continuous, unmanned intelligent production.

Regarding readheads, there was a concurrent comprehensive transformation in optical systems; the intricate optical route made up of numerous elements like light prisms and lens assemblies in conventional readheads got substituted by state-of-the-art technologies such as "single-field scanning", and the new breed of designs, led by the central optical system of the Heidenhain EnDat 3 interface encoder and the Renishaw ATOM series readheads, cut down on volume considerably and lessened sensitivity to installation clearances and twist angles via highly integrated optical parts and image-based sensing principles, which simplified installation and commissioning and also improved signal stability when exposed to machine vibrations [Moon2.1].

In general, during the past ten years, the development of high-precision linear grating scales mainly depended on sophisticated techniques like laser interferometric lithography and had made progress in three main aspects: material structure, functional combination, and optical systems; the design of the steel strip base was improved to enhance its impact resistance and installation allowance, meanwhile, the combination of incremental and absolute positions made it possible for the device to remember its position after being powered off, single-field scanning technology greatly decreased the size of the readhead and strengthened signal stability, these alterations promoted the constant development of grating scales towards higher precision, more dependability, and intelligence.

3.2 Application examples of laser displacement sensors in high-precision machining machines

Back around 2013, the majority of general-purpose laser sensors had a protection rating of IP65/IP67, making them not very effective at withstanding the force of high-pressure coolant or the invasion of metal dust within machining centers over long periods and being rather large and a hassle to install, frequently needing extra protective covers; however, starting from 2016, led by the KEYENCE LK-H series high-precision laser displacement sensors, the protection level was raised to IP67 (immersion-resistant), and an air purge interface was made a standard addition, and there was an internal airflow passage within the sensor which, once filled with clean and dry compressed air, could create a continuous positive-pressure air curtain in front of the lens, efficiently separating oil mist and chips so that the sensor could be firmly installed near the spindle or in the machining zone for long-term online measurement, and also to fit into extremely small spaces like tool magazines and spindle noses, the sensor's size was greatly decreased, for instance, the ultra-small sensor head in the Micro-Epsilon optoNCDT ILD series was just M12×30 mm, similar to an industrial proximity switch, but it could reach micrometer-level precision measurement, and meanwhile, the modular design where the controller and sensor head were separate became the norm, keeping the processing unit away from high-temperature and high-vibration areas and improving the overall system's reliability.

Progresses in optical systems and measurement concepts have also spurred the ceaseless evolution of laser displacement sensors, for example, the industrial employment of confocal chromatic technology has led to substantial breakthroughs, with the Precitec CHRocodile 2 series being a notable representative, this series employs a white-light source and a dispersing lens, which allows light of diverse wavelengths to focus at different locations along the optical axis, through analyzing the reflected wavelengths, absolute distance measurement could be attained and measurements at near-vertical angles were possible, thus surmounting the difficulties of measuring the thickness of highly reflective and transparent materials.

At the same time, the search for novel sensing mechanisms has been continuously broadening their scope of application; for example, the random laser displacement sensor founded on flexible gratings, as a newly-emerged technology, shows distinctive benefits, and this sensor integrates random laser medium with flexible grating structures, and the peak wavelength of its output laser spectrum reacts highly sensitively to tiny deformations (that is, displacements) of the grating, and this principle not only makes the sensor more sensitive but also because of its flexible substrate properties allows it to fit or adjust to non-flat and dynamically varying surfaces to be measured, thus offering a new possible solution for machine tools to measure the geometry of complicated curved surfaces or parts under vibration online [10].

In brief, within the past ten years, laser displacement sensors have attained IP67 protection, been able to purge the air, become miniaturized, and adopted modular design regarding protection and structure which enhanced their reliability in severe environments; in terms of measurement principles, confocal chromatic technology has surmounted the difficulties in measuring highly reflective and transparent materials and new principles like flexible gratings which have high sensitivity and conformability have broadened applications in complex curved surfaces and vibrating situations; sensors are constantly developing towards having greater adaptability, precision, and intelligence.

3.3 Application examples of laser interferometers in high-precision machining machines

Back around 2013, laser interferometers like the classic Renishaw's ML10 Gold model had a central system made up of a separate laser head and needed to be connected externally to various individual optical parts such as beam dividers, interference mirrors, and reflectors, and the optical arrangement was unwieldy and highly susceptible to minute vibrations and air currents so usually, it took experienced engineers several hours in a temperature-regulated workshop to troubleshoot; however, starting from 2018, along with the progress of technologies such as integrated interference mirrors, zero Abbe error design, and Absolute Distance Measurement (ADM), compact designs like Renishaw's XL-80 laser system and its XC-80 environmental compensation unit slowly became the norm and the size and weight of the laser head and interference mirror were greatly decreased, moreover, systems such as Automated Precision Inc.'s (API) XD Laser utilized a coaxial common path configuration enabling the measurement beam and reference beam to travel almost the same route thus cutting the sensitivity to external vibrations and air disruptions by 1-2 orders of magnitude and its interference mirror module combined linear, angular, and straightness measurement capabilities into one small unit with built-in optical elements and switched between measurement modes electronically rather than physically changing the mirror sets which sped up the setup time and enhanced reliability, and new-generation interferometers like Zygo's Verifire™ MST series and API's XD Laser also incorporated Absolute Distance Measurement (ADM) modules that could rapidly get the rough absolute distance of the mirror right at the start of the measurement and even if the light got interrupted during the measuring process, it could quickly bounce back and lock onto the proper whole number count of fringes attaining "light interruption continuous measurement" which was especially crucial in industrial settings with substantial vibrations.

In brief, within the past ten years, laser interferometers have experienced a substantial change from being separate and complicated systems to becoming integrated and highly interference-resistant designs, the new-era products led by Renishaw XL-80 and API XD Laser have considerably decreased their sensitivity to vibration and air flow due to the combination of interferometric mirrors and the coaxial common path design, the utilization of Absolute Distance Measurement (ADM) technology has made "interrupted light continuous measurement" possible which has significantly improved measurement dependability in industrial locations, and laser interferometers are shifting from laboratory-level precise instruments to effective diagnostic devices fitting for workshop settings.

4. Discussion

This research showed that a three-level precision system named "sensing-control-calibration" was jointly formed by high-precision grating scales, laser displacement sensors, and laser interferometers, driving machine tools to evolve towards intelligence, and in the previous ten years, the central iterative path had demonstrated structural combination, functional specialization, and information intelligence, and the cooperation among these three components regarding motion axis feedback, in-process measurement, and system accuracy calibration made up the key enabling technology for attaining stable machining at the submicron level.

However, this system is still confronted with crucial challenges like long-term dependability under severe working circumstances, time lags in decision-making during the fusion of multi-source heterogeneous data, and the expense and intricacy resulting from high precision throughout the whole system; future progress would concentrate on the chipification of sensors themselves and edge intelligence (for achieving diagnosis and compensation at the endpoint side), the standardization of modules, and plug-and-play integration for reducing obstacles, as well as in-depth combination with digital twin technology for optimizing and predicting precision in the virtual space, thus heading towards resilient and adaptable intelligent manufacturing.

5. Conclusion

This piece presents a methodical expounding on the tenets, functions, and development paths of three key types of optoelectronic sensors utilized in high-precision machine tools and the technological progress of these sensors followed an internal logic shifting from separate and complicated setups to combined and smart systems and from general measuring to functions designed for particular applications fitting specific working situations and together these improvements set the limits of machine tool abilities regarding nanoscale feedback, real-time detection, and system adjustment and when confronted with issues about dependability, combination, and cost-effectiveness, the future direction clearly led to a further merging of electrical and mechanical and optical technologies along with the addition of built-in intelligence and sensors would act as inborn intelligent parts instead of being added as after-market pieces thus significantly strengthening the capabilities of machine tools and consequently the whole manufacturing system which would drive the continuous forward movement of high-end manufacturing towards greater precision, more self-sufficiency, and wider availability.

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