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Research paper

A 3D nano-resolution scanning probe for measurement of small structures with high aspect ratio

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ABSTRACT

A tactile 3D scanning probe based on differential detection of astigmatic focus error is developed using commercial DVD optical pick-ups as sensing elements, and proposed for measurement of small structures with aspect ratio up to 30:1. The conflict between resolution and lateral size of the probe is resolved by a design of parallel kinematic flexible suspension with vertical and orthogonal layout of sensing elements, and common mode interference is significantly suppressed by differential detection of astigmatic focus error signals. Experimental results show that the displacement resolution of the probe is up to 1 nm with a ϕ3 mm probing ball and a 150 mm long stylus. It is therefore concluded that the probe proposed is a solution for measurement of structures with high aspect ratio with high precision and low cost.

1. Introduction

A 3D scanning probe is one of the most important units in coordinate measuring machines (CMM) and other dimensional measuring instruments. Traditional probes based on serial kinematic flexible suspension which allows movement of probing balls along three translational axes [1,2], such as Zeiss active probes VAST, Leitz passive probe TRAX and Renishaw passive probe SP80, usually feature high structural complexity and high cost. Meanwhile, probes based on parallel kinematic flexible suspension which allows movement of probing balls along one translational axis and around two rotational axes [3,4] have relatively simpler structure and lower technical difficulty, and have been developed by lots of researchers and developers. On the other hand, considering shortcomings and limits of traditional principles of displacement transducers such as resistive, inductive/transformative and capacitive principles, photoelectric detection technology attracts researchers' attention and much research has been done in recent years. For example, Renishaw [2], Fan et al. [5], and Li et al. [6] developed probes using incremental scales including diffraction gratings and miniaturized interferometers as displacement transducers to meet special performance requirements on precision, size and dynamic properties. Pril et al. [7] and Bosbach et al. [8] used PSDs to monitor the position of probing balls based on optical triangulation principle, thus to achieve ultra-small probing force and moving mass as well as excellent dynamic response.

During development of scanning probes based on photoelectric detection, cost is always a key consideration. In 2007, Chu et al. [9] firstly introduced commercially DVD optical pick-ups as displacement transducers during development of micro-probes. Hermann et al. [10] and Fan et al. [11] also did deep research on this method. DVD optical pick-ups become a new attractive option as displacement transducers in scanning probes because of their nanometer resolution and very low cost.

In recent years, resulting from breakthrough in non-traditional machining technologies, small structures with high aspect ratio such as small deep holes are more and more widely used in some sophisticated instruments and advanced equipments, with which fuel, energy and information can be transmitted through a long distance with a simple structure and light weight. For example, a large number of small deep holes with diameters of several millimeter and length-to-diameter ratio above 10 are manufactured in the fuel jetting mechanism of rocket engines. The measurement of such small structures with high aspect ratio presents challenges to existing probes on measurability, precision and measurable depth, and the conflict between resolution and lateral size of probes with traditional layout of sensing elements becomes especially serious.

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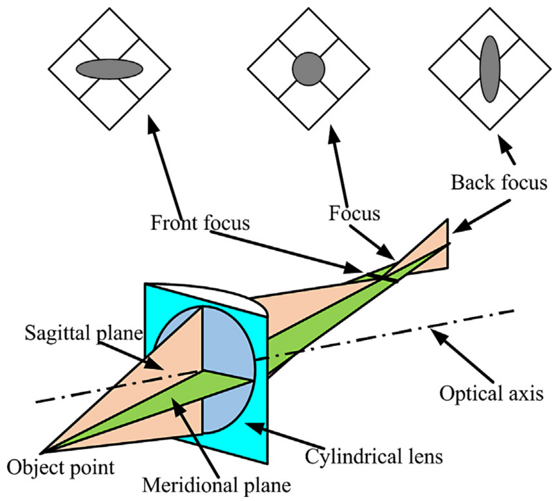

Fig. 1. Schematic of astigmatic focus error detection.

Therefore, a 3D scanning probe is proposed using commercial DVD optical pick-ups as sensing elements in this study. Through a structural design of parallel kinematic flexible suspension with vertical and orthogonal layout of sensing elements, and differential detection of astigmatic focus error signals, a low cost 3D scanning probe with nanometer resolution and measurable aspect ratio up to 30:1 is developed.

2. Principle

2.1. Astigmatic focus error detection for displacement transducing

As shown in Fig. 1, astigmatism is a kind of monochromatic aberration caused by misalignment of meridional and sagittal image points. In the DVD optical pick-ups used for the present study, astigmatism is produced by placing a cylindrical lens in front of a four-quadrant detector. The shape of the image on the four-quadrant detector varies with respect to the axial position of the four-quadrant detector. By detection of the light intensity distribution on each quadrant of the detector, the displacement of one of the object, cylindrical lens and detector can be determined while the other two are kept still. For the present study, the cylindrical lens and the four-quadrant detector are kept still, while the part to be measured serves as a movable object.

As described in Section 2.2, DVD optical pick-ups are constructed into an orthogonal and differential layout in this study. So the common-mode interference resulted from mechanical, electrical and optical factors, which often further resulted from environmental variation around the probe [12] can be counteracted during differential detection of astigmatic focus error signals, and anti-interference performance of the probe is significantly improved. Furthermore, lateral displacement resolution of the probe is improved by 1/2 because amplitude of the output signal is doubled through differentially detection.

2.2. Vertical and orthogonal layout of sensing elements

A structural illustration of a probe with parallel kinematic flexible suspension and horizontal layout of sensing elements is shown in Fig. 2. The design of parallel kinematic flexible suspension is composed of a cross rigid beam and four end-constrained elastic diaphragms, allowing movement of probing balls along one translational axis and around two rotational axes. Ignoring deformation of the cross rigid beam and stylus during probing, displacement

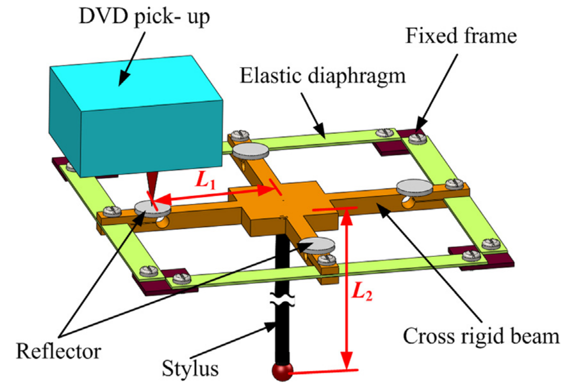

Fig. 2. Horizontal layout of sensing elements [9,14].

transfer ratio R is defined as the ratio of $L1$ to $L2$, where $L1$ is the distance between the center of the reflector and the stylus axis, and $L2$ is the distance between the center of the probing ball and the plane defined by elastic diaphragms, i.e. valid length of the stylus.

It is clear that the increase of $L1$ will increase the displacement transfer ratio R, and further improve the displacement resolution of the probe. However, for measurements of small structures with high aspect ratio, the valid length of stylus $L2$ should be large, which means very large $L1$ is needed to achieve high resolution, resulting in very large lateral size of the probe. For example, during measurement of a small deep hole which is 150 mm in depth, if the displacement resolution of the sensing element is 1 nm, in order to achieve a resolution better than 1 nm, $L1$ should be longer than 150 mm and the lateral size of the probe is larger than 300 mm, which is unacceptable for most CMMs and other dimensional measuring instruments.

So it can be concluded that the horizontal layout of sensing elements is more suitable for development of micro-probes whose lateral size is limited because of small length of styli, but not suitable for probes developed for measurement of small structures with high aspect ratio. Considering CMMs and other dimensional measuring instruments usually have strict limitation on lateral size while loose limitation on vertical size for probes, e.g. shafts and probe holders are often assembled onto Z axis sliding guides of CMMs, a structure design of parallel kinematic flexible suspension with vertical and orthogonal layout of sensing elements is proposed.

As shown in Fig. 3, a reflector frame made of light material is fixed on the cross rigid beam. Five reflectors are fixed on five side faces of the reflector frame. Each reflector corresponds to a single DVD optical pick-up (only three DVD optical pick-ups are shown in Fig. 3 for clarity), constructing a kind of vertical and orthogonal layout of sensing elements. Although in principle three DVD optical pick-ups would be enough, five DVD optical pick-ups are used for differential detection in horizontal directions without increasing the probe size. For this new structure proposed, ignoring deformation of the cross rigid beam and stylus, displacement transfer ratio R is the ratio of $L1$ to $L2$, where $L1$ is the distance between the center of the reflector and the plane defined by elastic diaphragms, and $L2$ is the valid length of the stylus. The resolution of the probe could be easily improved by increasing $L1$ and vertical size of the probe. The lateral size of the probe is at least $2L1$ with a horizontal layout of sensing elements, in contrast, the vertical size of the probe is at least $L1$ with the vertical layout proposed, so much less measurement volume is reduced and the size of the probe is more acceptable.

Before the probing ball touches the part to be measured, emergent light from five DVD optical pick-ups is focused on surfaces of corresponding reflectors. When the probing ball touches the part,