Study on the Mechanism of an Innovative High-speed Scanning Miniature Nano-measuring Probe

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Abstract. The primary purpose of this research is to adopt a commercially available DVD pickup head and modify it to become a high-speed scanning nano-measurement probe. With the principle of astigmatism the probe can execute the autofocusing motion by an imbedded voice coil motor (VCM) following the height change of the tested object in the vertical Z-direction. Given high precision triangular current signal with appropriate frequency to the input ports of tracking, the same VCM can be moved along the lateral X-direction for profile scanning. Firstly this paper presents the structure of DVD pickup head, the theory of autofocusing and auto scanning, and the developed controller. Then experimental setups and accuracy calibration will be introduced. In order to achieve a bi-directional precision measurement in autofocusing and scanning, this study has developed the hysteresis error compensation scheme by a DSP-32 integrated system. In association with a high precision linear stage in Y-direction, this high precision micro/nano optical probe can measure the 3D profile of the miniature object successfully in fast speed.

Introduction

Technologies of high-precision inspection have been developed in recent years all over the world, among which the probe design is the key issue of all measurement systems. As far as in the development of ultrahigh precision CMM with nanometer accuracy in progress is concerned, SPM probe was adopted by NIST, MIT in the United States and SIOS Co. in Germany. [1-2]. The touch triggered probe (TTP) with light detector was developed by Tokyo University in Japan, PTB in Germany, BUPE in South Korean, and NPL in UK [3-5]. The structure of all the above probes is very complex and expensive. In addition, the stylus tip of TTP is still limited in its physical size to unable access the dimension below 50μm. This research aims at studying the characteristics of autofocusing and tracking on a commercially available DVD pickup head and modifying it to achieve a high-speed scanning nano-measurement probe with optical tip size below 1μm.

Structure of the Probe System

Market available DVD pickup head as shown in Fig. 1 (such as HITACHI HOP-1120) mainly contains the following components: laser diode, grating, polarization beam splitter and 1/4 λ plate, four-quadrant photodiode IC, objective lens and voice coil motor (VCM), as shown in Fig. 2. Our research purpose is to fully use the properties of these components with advanced skills to convert the pickup head into a non-contact measuring probe.

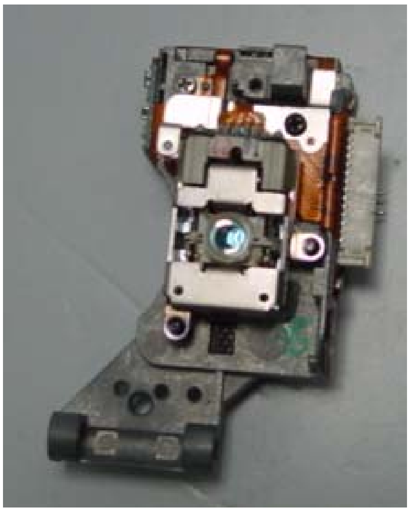

Fig.1 DVD pickup head

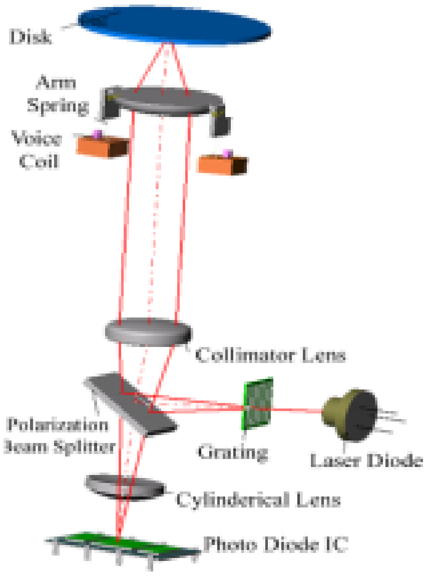

Fig.2 The elements of the DVD pickup head

Laser Diode. A low-power laser diode (about 5 mW) that emits light at 630 nm to 650 nm is integrated in the DVD pickup head. The laser beam can be collimated and then focused to a small spot at the diffraction limit [6]. Because of the wavelength shift of several nanometers due to temperature effect, the auto power compensation (APC) circuit is required [7].
Grating. Due to the diffraction effect the laser beam will transmit the grating plate and generate three diffractive beams. The main beam of the zero-order is use for autofocusing the disk while two side beams of the ±1-order is used for auto tracking of the disk in CD.
Objective Lens. Presently DVD optical pickup systems mostly use holographic optical elements (HOEs) for focusing the laser beam on a diffraction-limited spot. This lens consisting of two aspheric surfaces on a single piece of glass has fairly large numerical aperture about 0.65.
Four-quadrant Photodiode. The photodiode is consisted of four parts. Each part can detect the projected light intensity and transform to proportional current. Combination of the results in proper way can produce the focus error signal (FES) and tracking error signal (TES) for use.
Voice Coil Motor. Generally, the voice coil motor (VCM) system consists of a mobile coil and a perpetual magnet. The VCM built in to the pickup head plays the role of a driving part, which carries the objective lens. The FES and TES received by the photodiode will output current signals to generate Lorentz forces, which move the objective lens for autofocusing and tracking purposes respectively.

Autofocusing Principle

The objective lens is mounted on the voice coil motor that is used to drive the lens toward or away from the tested surface according to the received FES to maintain focus at all times. When the surface is out of focus, such as the place at plane1 or plane3 shown in Fig. 3, the returned beam forms an elliptical spot on the detector. This elliptical spot may asymmetrically illuminate four quadrants A, B, C and D of the detector. Therefore, the combination signal of [(A+ C) - (B + D)] provides a FES, which then feeds back to the VCM for maintaining focus automatically [8].

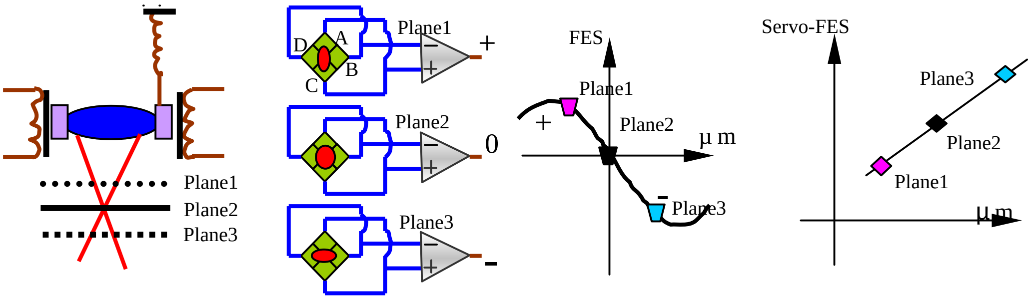

Fig.3 The principle of autofocusing theory

Automatic Scanning Principle

The signals on an optical disk are recorded along consecutive concentric circular tracks. Manufacturing errors, disk eccentricities, dynamic errors, and thermal expansion of the DVD system will cause wobble fluctuation of the disk yielding to out of the track position as the disk is rotating. The focused spot diameter is only about 1μm and cannot always keep on the right track position at all times. Therefore an automatic tracking scheme has to be applied. The main beam of zero-order diffraction plays the roles of FES and autofocusing, while two side beams of the ±1-order is used for auto tracking of the disk and detects the wobble and the out-of-track by the DPD (Differential Phase Detection) technology. The four-quadrant photodiode will output a tracking error signal (TES) to the VCM. This feedback signal can then adjust the objective lens in the lateral direction. In this research the characteristics of disk tracking is fully utilized by given high precision triangular current signal with appropriate frequency to the input ports of tracking, the VCM can be moved along the lateral direction for profile scanning.

Experimental Setup and Accuracy Calibration

FES S-curve. If the objective lens is not in focus, the reflected spot on the detector is elliptical through which the FES voltage can be generated in the range of focal length. In the measuring process the objective lens is fixed so as to keep the constant focal range. The designed circuit board collects and amplifies the signals from the four-quadrant photodiode, then outputs the FES signal to a digital multimeter (KEITHLEY 2700). The pickup head is moved by a linear stage at steps about 0.1μm and calibrated by an HP5529A interferometer, as shown in Fig. 4. Calibrated results are shown in Fig. 5. A clear S-curve with steep linearity can be found in the range of 70~85 μm.

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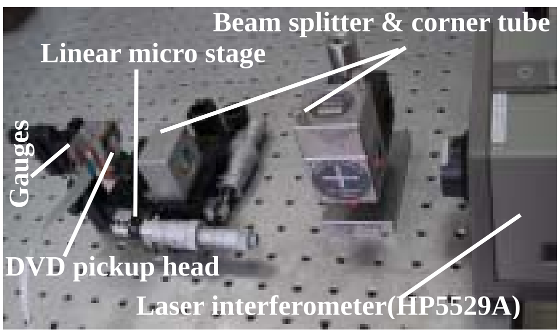


Fig.4 The setup of measuring FES

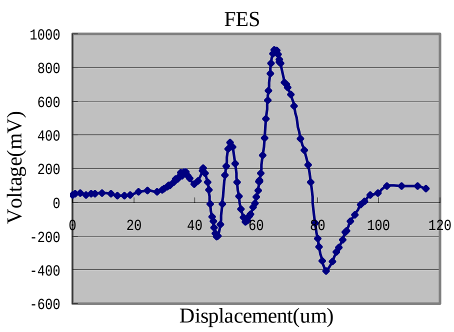


Fig.5 Calibrated S-curve

Hysteresis Compensation. When a ferromagnetic material is magnetized in one direction, it will not relax back to zero magnetization when the imposed magnetizing field is removed. It must be driven back to zero by a field in the opposite direction. If alternated magnetic fields are applied to the material, its magnetization will trace along a hysteresis loop, as shown in Fig.6. This phenomenon happens the same in the VCM system of the pickup head. Hysteresis motion can cause a number of undesirable effects, including loss of stability, limit cycles and steady-state error. Many hysteresis error compensation models have been proposed in PZT motion control, such as Preisach model [9], Neural model, Jiles-Atherton mode, Ising model, Bouc-Wen Model, Stoner-Wohlfarth model, etc. Among which researchers mostly apply the Preisach model.

In this study, we use Preisach model to realize hysteresis errors compensation. The mathematical formulation of this model on piezoelectricity actuators is defined as

$$X(t) = \iint_{\alpha \geq \beta} \mu(\alpha,\beta)\gamma_{\alpha\beta}[u(t)]d\alpha d\beta \,, \tag{1}$$

Where $X(t)$ is the output response, $u(t)$ is input, $\gamma_{\alpha\beta}[u(t)]$ is hysteresis element, $\mu(\alpha,\beta)$ is the power-weight of $\gamma_{\alpha\beta}[u(t)]$ (often being 1) and α , β are the switch-values of ascend and descend to $u(t)$ respectively.

The value of $\gamma_{\alpha\beta}[u(t)]$ is set to 1 when $u(t)$ is above α , and is set to zero when $u(t)$ is below β . Fig.7 illustrates a useful graphic interpretation. More and more $\gamma_{\alpha\beta}[u(t)]$ change to 1 when $u(t)$ is continuously increased when $0 \leq t \leq t_1$. $X(t)$ is the area $S(\alpha_1\beta_1)$ referring to Eq. (2) which is deduced from Eq.(1). When $u(t)$ decreases during $t_1 \leq t \leq t_2$, $X(t)$ is the region $S(\alpha_1\beta_1) - S(\alpha_1\beta_2)$. If $u(t)$ is increased to $u_1(t)$ during the time $t_2 \leq t \leq t_3$, $X(t)$ becomes the area $S(\alpha_1\beta_1) - S(\alpha_1\beta_2) + S(\alpha_2\beta_2)$. If $u(t)$ continues to decrease till it comes to $u_2(t)$ when $t_3 \leq t \leq t_4$, $X(t)$ is $S(\alpha_1\beta_1) - S(\alpha_1\beta_2) + S(\alpha_2\beta_2) - S(\alpha_2\beta_3)$. In this study, $X(t)$ is the output displacement of VCM, and $S(\alpha_i\beta_j)(i = j = 1,2\cdots N-1)$ is the displacement of each step in measuring process, the universal formula can be deduced as Eq. (3) when $u(t)$ is increasing at the last step, or as Eq. (4) when $u(t)$ is decreasing at the last step.

$$X(t) = \iint_{S(\alpha_1\alpha_1'\beta_1)} \mu(\alpha,\beta)\gamma_{\alpha\beta}[u(t)]d\alpha d\beta = S(\alpha_1\beta_1) \tag{2}$$

$$X(t) = \sum_{K=1}^{N-1}[S(\alpha_K\beta_K) - S(\alpha_K\beta_{K+1})] + S(\alpha_N\beta_N) \tag{3}$$

$$X(t) = \sum_{K=1}^{N-1}[S(\alpha_K\beta_K) - S(\alpha_K\beta_{K+1})] \tag{4}$$

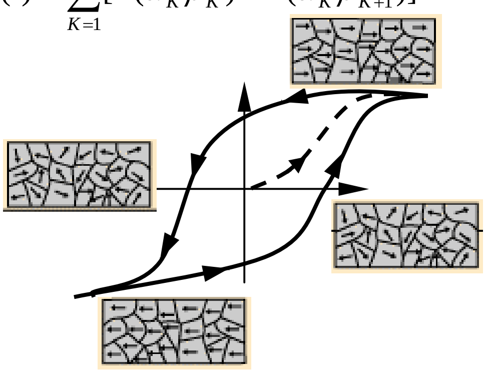


Fig. 6 Typical hysteresis curve

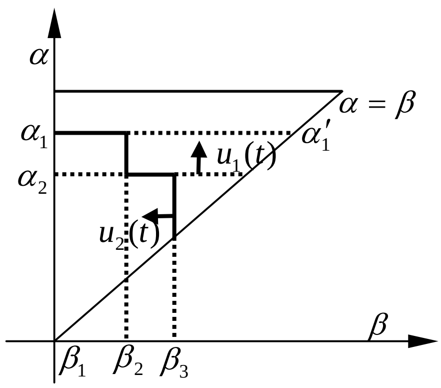


Fig.7 Geometric illumination of the Preisach model

Focusing Characteristic. Because of the narrow active range of FES, about 15μm, a special focusing operation is needed. The system must move the lens to search the "S-curve" by a servo controller. Once it is detected, the servo feedback this signal to the actuator, thereby locking the system in focus. In this experiment the data are acquired at every interval of 0.1μm. After hysteresis compensation the servo-voltage is linear to the displacement of VCM in 600μm by experiments, as shown in Fig.8. Fig.9 shows the developed servo controller board.

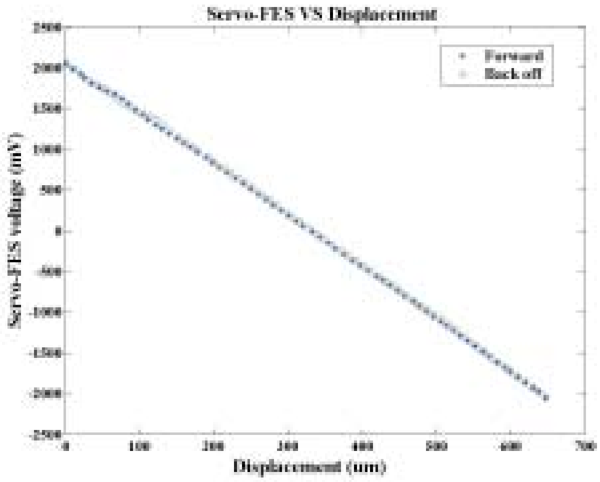
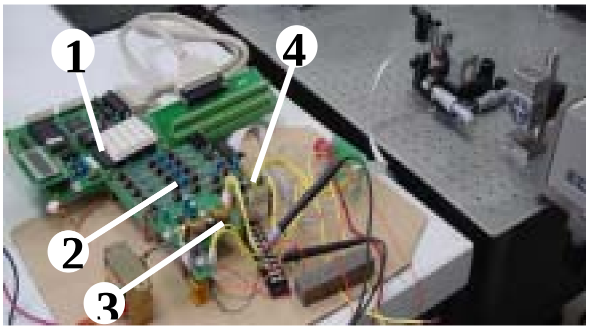


Fig.8 VCM input voltage vs. displacement.



(1) DSP-32 (2) Developed operation circuit (3) Fiducial power circuit (4) Auto power compensation (APC) circuit

Fig.9 The configuration of servo-focusing controller.

Auto Scanning Characteristic. The tracking error signal (TES) is a position error signal of the focused spot relative to the measured track of the disk in DVD. In this research, the relationship between the input tracking servo voltage and the displacement output of the objective lens is studied. Given high precision triangular current signal changing from positive to negative with appropriate frequency about 1 HZ, the VCM can move the lens along lateral direction repeatedly for scanning. In this experiment the beam spot movement is measured by a CCD equipped microscope, as shown in Fig. 11. Fig.10 shows the diagrams of experimental results. Good linearity can be obtained in all different scanning range up to 300 μm.

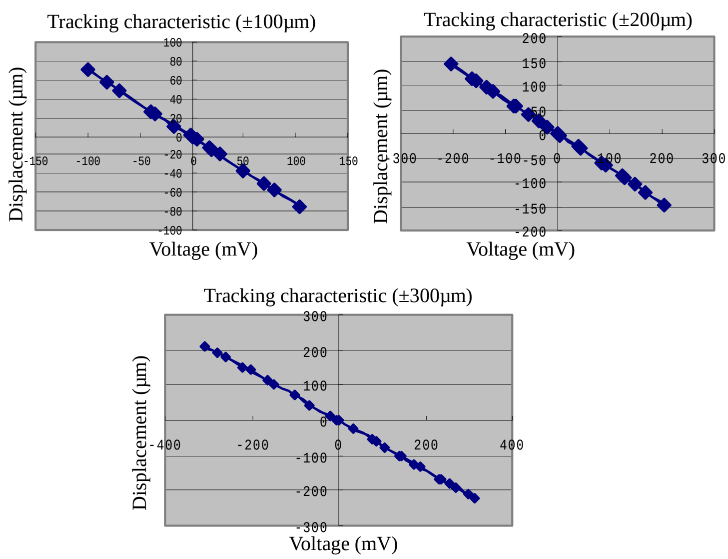


Fig.10 The diagrams of scanning characteristic

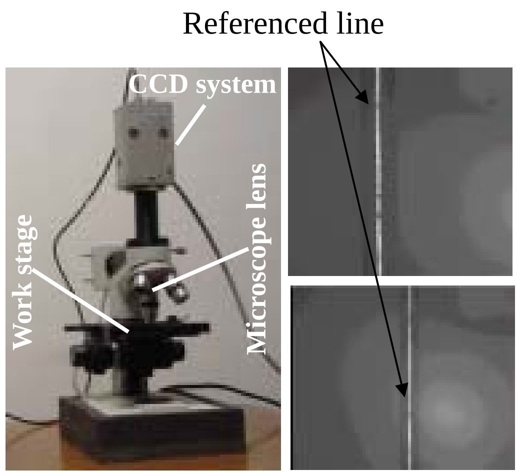


Fig.11 The setup of measuring scanning characteristics

Applications

As shown in Fig.12, three gauges are overlapped together for verification measurement. Giving the tracking input ports about every 10mV and recording the voltage of servo-FES, the results of measurement are shown in Fig.13 from which a clear step height about 15μm is obtained.

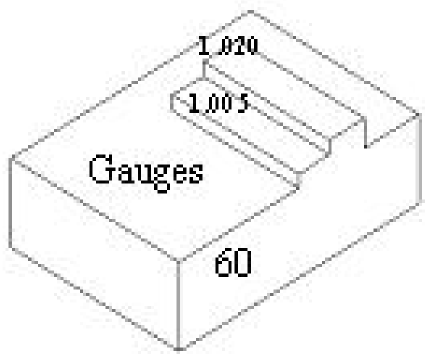


Fig.12 Step height measurement

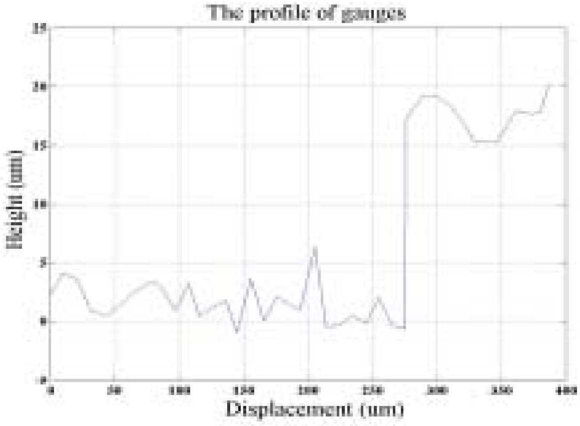


Fig.13 Results of measurement

Conclusions

The primary study on the combination of autofocusing and auto scanning performances of a nano measuring probe, converted from a commercial DVD pickup head, has demonstrated that the range of bi-directional horizontal scanning is ±300 μm, the resolution is less than 50nm, and the accuracy is better than 100nm. The measuring range of autofocusing motion is also ±300 μm, and the resolution is less than 10nm with FES. The probe could accurately measure the profile of micro objects.

References

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