A circuit design of high-precision micro-displacement sensor system for DVD pickup head

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***Abstract*—The voice coil motor VCM will be removed in the structure, and we have designed a new high-precision displacement measurement of the circuit, which mainly includes focus error signal of the DVD (S curve) processing circuit, LD control circuit, open signal logic circuit, S curve linearity zone selection and location to determine the circuit, the normalized circuit and other components, to achieve the accurate measurement of the micro-component (geometric dimensions for a few millimeters to a few microns, more precision parameters for the micro nanometer scale). It has simple structure, good linearity, high resolution, anti-interference capability, measuring in any environment., and other outstanding features.**

***Key word*—DVD Optical Pickup, Focus Error Singal, LD control, Linear Area, Normalized, Micro/Nano Measuring**

I. INTRODUCTION

Optical non-contact probe is fit for measuring small, thin, soft parts, and it will not cause abrasion damage for the fragile surface of the workpiece. It will also not lead to measuring rod and local deformation of the surface affected, correcting the correct reading of the coordinates, while contact forces oppress the surface. It even eliminates the time delay for trigging and the wrong readings resulting from institutional inertia. In addition, because the ball volume is very small, there is no need to compensate for the impact of probe radius. These factors make non-contact probe important position increasingly, wide application range today[1].

DVD pickup head, as a non-contact optical measurement probe [2], own the laser source, optical design detectors, etc. Due to the integrity of the system and focus features, we only develop appropriate modifications and improvements in control method, it can become a practical non-contact probe. From the precision, micro-probe no longer applies, but more sophisticated probe remains high cost and complexity. Therefore, it is fully justified to develop a new low-cost high-precision probe for measurement. The research, for the purpose of building a new high-precision micro-nano measuring system, we could improve the DVD pickup head, and develop to adapt to a variety of measurement requirements of precision measurement systems.

II. PRINCIPLE AND DESIGN IDEAS

A. Operating principle for DVD pickup head

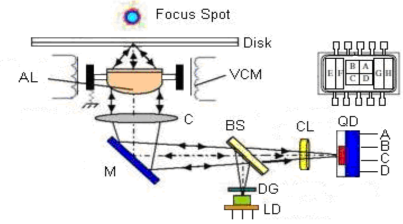

Fig.1 The internal structure of a typical DVD pickup head. VCM: voice coil motor. AL: aspheric lens. C: collimator. M: mirror. BS: beam splitter. CL: cylindrical lens. QD: quadrant detector. ABCD: four signal outputs of the QD. DG: diffraction grating. LD: laser diode.

The LD emits about 0.5mW red laser beams (central wavelength of 650 nm) [3]in power. Passing through a grating the light diffracts into three beams, as shown in Fig.1. These beams pass through a polarized beam splitter, mirror, collimating lens and holographic lens, and finally focus on the measured surface. The beams are then reflected back along the original path and pass through a cylindrical lens, and finally project onto the four-quadrant detector, which will output four voltage signals V_A, V_B, V_C, V_D according to the main beam spot position in each quadrant. The voltage signals are, by calculated, turned into focus error signal (FES) which is used to drive the VCM. The VCM shifts the objective lens until the focal point is back to the object surface. The amount of VCM movement is recorded and equivalent to the profile change of the object. The FES is expressed as

$$FES = (V_A + V_C) - (V_B + V_D) \tag{1}$$

B. *FES characteristics*

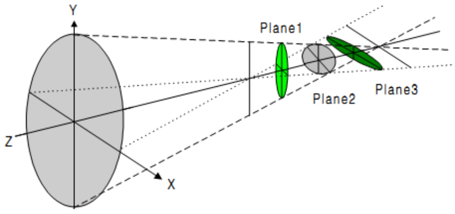

Fig.2 Schematic diagram of the astigmatic method

This research employs the Hitachi DVD pickup head with model number HOP-1000. Its focus theory is the astigmatic method[2, 4, 5, 6-8]. As shown in fig.2, when the object plane is located inside or outside the focal plane of the objective lens the light on the four-quadrant detector will become an elliptical shape (plane 1, plane 3), and the direction of two elliptical shapes is perpendicular to each other. If the object is right on the focus point, the light image will be in a circular shape (plane 2). Using proper signal processing, the focus error's S-curve can be obtained by plotting the voltage difference between the paired photodiodes.

III. SIGNAL PROCESSING CIRCUIT

A. *Amplifier circuit for FES*

In the disc systems, the VCM adjust the lens position according to △Z, the distance which is expressed from the object surface to the beam focal plane. When △Z value is zero, the disc is in focus position. In this project, we use probe offset to reflect the location of the object. Thus we shall remove the VCM so that the movement distance of the probe is △Z.

The DVD pickup head we choose could output voltage signals V_A, V_B, V_C, V_D, $(V_A+V_B+V_C+V_D)$, and control signal LD keeping laser power stable. The sum signal (SS) is expressed as

$$SS = (V_A + V_B + V_C + V_D) \tag{2}$$

By measuring, the value of V_A (V_B, V_C, V_D) is quite small (millivolt); the value of SS is about 1.5V, so we must amplify the value of V_A (V_B, V_C, V_D), as shown in Fig.3

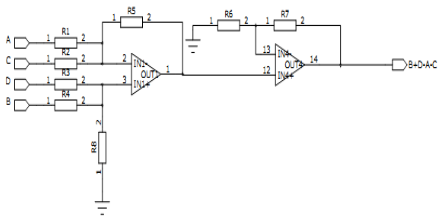

Fig.3 Pre-amplifier circuit for FES

B. *Automatic power control (APC) circuit*

The main function of APC circuit could keep LD power constant. The value of V_A (V_B, V_C, V_D) is different as LD power is different, so the LD light power determines the sensitivity of DVD output signals. Therefore, so as to get a good S-curse, LD power must remain unchanged in the whole measurement process.

The photodetector PD is built-in DVD pickup head to detect LD luminous intensity technically. Pin PD and pin LD are of the connection block. When the value of PD is changed, LD power has yet been changed. The circuit automatically adjusts PD outputs by the real-time feedback to maintain PD at its original value, as is shown in Fig.9.

C. *Gate signal logic circuit*

(An innovation point in the research) FES curve can be used to measure when it only remains in linear region. By the preceding analysis, we may find SS amplitude is higher than other regions of FES curve, when the curve enters into the linear region. Thus, we just find out the value of SS corresponding to the value of FES curve peak. Then, the value of SS is inputted into a comparator to get a square wave signal, and the signal drives an analog switch. When the square wave signal remains at high level, the switch is open, FES curve must remain in the linear region, otherwise, no FES curve. So the FES curve could be achieved only in the linear region.

D. *Select the linear region and judge the location circuit*

(Another innovation point in the research) Control signal is from the output of Gate signal logic circuit. When FES curve is above zero, a pulse is outputted, otherwise there is no output.

E. *Normalized circuit*

As mentioned above, when material of the measured surface is different, the reflected light intensity will be different, so whether the amplitude of FES or SS is changed. If we just process FES curve, the value of SS need to be re-calibrated when the object is changed every time. It will bring great trouble, but we could not measure without calibration. Therefore, the normalized focus error signal (NFES) is introduced to eliminate the effect caused by the reflectance of the object surface.

The NFES is expressed as

$$NFES = \frac{FES}{SS} = \frac{(V_A + V_C) - (V_B + V_D)}{(V_A + V_B + V_C + V_D)} \tag{3}$$

Of course, if the input signal is truncated focus error signal (TFES), the output signal is truncated normalized focus error signal (TNFES), as shown in fig and Fig.4

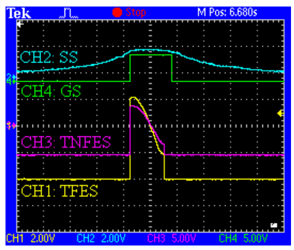

Fig.4 The TFES and the synchronized TNFES measured by the flat mirror surface. Note that voltage values of four curves represented by different a grid. SS: sum signal. GS: gate signal.

IV. EXPERIMENT AND ANALYSIS

A. *Experimental establishment*

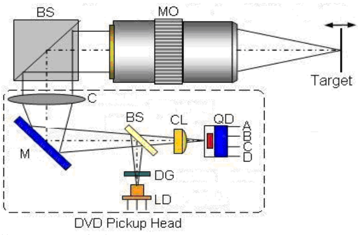

Fig.5 Schematic diagram of the FES measurement system. MO: microscope objective. BS: beam splitter. C: collimator. M: mirror. CL: cylindrical lens. QD: quadrant detector. ABCD: four signal outputs of the QD. DG: diffraction grating. LD: laser diode.

In the FES measurement system, the VCM and aspheric lens have been removed from DVD laser head. The collimated beams pass through the MO (Mitutoyo Inc. M Plan Apo 10× N.A. 0.28), and finally focus on the measured surface. When the object is relative to different positions of the focal plane, the FES will be following the S-curve theory. In addition, the voltage is 0V in the focus and ±2.5V in the defocus.

The NFES and the synchronized FES are measured by the flat mirror surface with a high reflectance and the glass surface with a quite low reflectance, respectively, as shown in Fig.6 (a) and (b). The voltages of peak-to-valley ratio (P-V) of NFES and FES (i.e. P-V(NFES)/P-V(FES)) is about 2 for the mirror surface, while about 17 for the glass surface; therefore the extremely low reflectance of glass surface is eliminated by the NFES. In addition, the NFES slope nearly coincides with the FES slope within the focus point, lock-on range and the acquisition range.

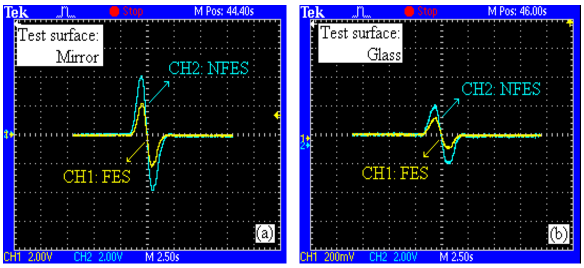

Fig.6 (Color online) The NFES and the synchronized FES measured by (a) the flat mirror surface and (b) the glass surface. Note that voltage values of four curves are represented by different a grid for (a) and (b), especially FES voltage values.

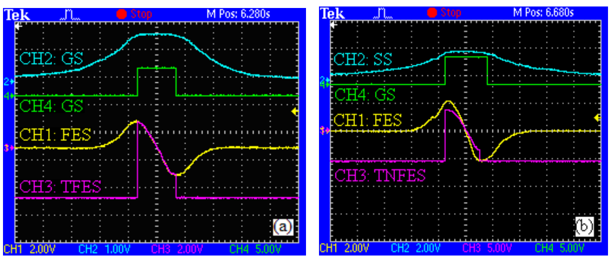

Fig.7 (Color online) (a) The TFES or (b) the TNFES is obtained if the GS is true (i.e. at a high voltage value) when the SS value is larger than the threshold value. Note that voltage values of curves represented by different a grid in two figures.

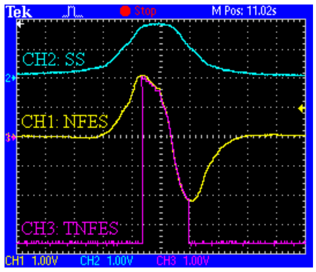

Fig.8 (Color online) The NFES, the SS and the synchronized TNFES measured by the flat mirror surface. Note that voltage values of three curves represented by different a grid.

From the Fig.7 and Fig.8, we found that a voltage value of FES (or NFES) corresponds to two positions of the measured surface (expect peak value) due to the non-monotonicity of the FES (or NFES). Nevertheless, we may also discover that the SS reaches a maximum value and the shape of the SS is symmetrical about the value, when the FES crosses the zero point. According to this phenomenon, we have designed "Gate signal logic circuit". The resistance of rheostat was regulated to set the threshold value, thus it will be effective to truncate the FES (or NFES), then obtained the monotonic FES (or NFES). If the SS is larger than the original value, the circuit outputs a high voltage (i.e. logical truth), otherwise a low voltage (i.e. logical false). When the circuit retains logical truth and the FES is inputted to "select and judge circuit" or the NFES to "normalized circuit", respectively, the TFES or TNFES will be obtained. In addition, although the FES (or NFES) could produce more than one zero crossing points within the acquisition range, the TFES (or NFES) is not affected. Note that the TFES (or NFES) is retaining negative voltage (about 4V) within the defocus range. It is deliberately designed to guarantee that obtain one zero crossing point excellently.

B. *laser power effect*

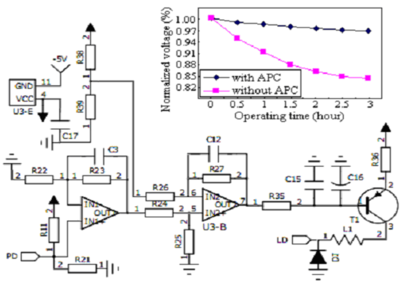

Fig.9 (Color online) APC circuit. Insert: The normalized LD output voltages against operating time with APC and without APC.

Because of the laser diode power drift in the DVD pickup head, the maximum value of SS may be changed and the original threshold will also be changed along with it. Previous analysis of the circuit has shown that[4], the major reason for the LD power drift is that the LD output power is very sensitive to the surrounding temperature. In the modified DVD pickup head used in the system, the laser power detector (PD) is embedded inside the pickup head and used to continuously monitor the LD output power as feedback from the designed automatic power control (APC) circuit to retain the stability of the LD output power. The circuit schematic diagram is shown in Fig.9 which shows that the stability of the LD output power with the APC circuit has been improved a lot compared with that without the APC circuit, and the normalized voltage of the LD with the APC circuit is reduced by only about 3% after an operating time of about three hours. Therefore, the effect of the LD power drift on the threshold value in the system is obviously small.

C. Analysis of standard deviation, accuracy and resolution

The experiment of measuring TNFES has been repeatedly on a flat mirror nine times, and the TNFES curves are plotted in Fig.4. We found that the nine curves almost coincide with each other due to exceptional good repeatability. The sensitivity, standard deviation, measurement error and background noise are tabulated in table 1. The average sensitivity is 70 mV/µm, while the sensitivity within the linear range of TNFES is about 120 mV/µm. The average standard deviation is 2.9 mV. Thus, in terms of length, the average standard deviation is 0.041 µm (2.9/70). In the system, a 16-bit 250 kHz A/D converter (NI PCI-6221) of ±10V operational voltage was used to interface to a computer. One digital of the A/D corresponds to 0.305 mV. Thus the average resolution of TNFES could reach 4.4 nm (0.305/70). The measurement error, determined as the product of average standard deviation and average sensitivity inverse[5], is 41.6 nm on average. However , the background noise of TNFES will enlarge the error. The average background noise was measured to be about 6.7 mV, which corresponds to 95 nm (6.7/70) on average and 55 nm (6.7/120) within the linear range of TNFES. That means the average measurement error could reach 95 nm. Nevertheless, in the process of autofocus, the determination of the best focus within the depth of focus (DF) of the microscope objective is most important. The DF of the microscope objective we used is ±3.5 µm. Within this range, the measurement error is 55 nm. Determination of the best focus within the DF range of 7 µm with an accuracy of 55 nm is absolutely no problem.

Therefore, the measuring system can be verified with a dynamic range of 190 (±95) µm, average sensitivity of 70 mV/µm, average standard deviation of 0.041 µm, displayed resolution of 4.4 nm accuracy of 55 nm.

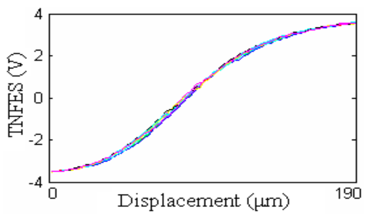

Fig.10 (Color online) Repeatability test results of TNFES for nine times

Table 1. Repeatability test results

TNFES	Average Sensitivity (mV/µm)	Sensitivity of linear Range (mV/µm)	Standard Deviation (mV)	Measurement Error (nm)	Noise (mV)
1	69.97	123.8	1.89	27.0	6.56
2	69.81	122.8	3.27	46.8	6.38
3	70.14	124.3	6.10	86.9	6.72
4	70.04	125.0	1.28	18.3	7.03
5	70.09	117.8	3.07	43.8	6.95
6	70.02	117.2	1.51	21.6	7.09
7	70.10	117.7	4.76	67.9	6.55
8	70.06	117.4	2.85	40.7	6.32
9	69.60	117.0	1.47	21.1	6.75
Average	69.98	120.3	2.91	41.6	6.71

V. CONCLUDING REMARKS

This system has a measuring range up to 200 µm with accuracy about 0.2 µm, a resolution of 0.1 µm and standard deviation of 0.2 µm on average. The hardware cost of the developed system is about US$100, which is significantly less than most commercial products with similar function and capability. The measuring system has a dynamic range of 190 (±95) µm, average sensitivity of 70 mV/µm, average standard deviation of 0.041 µm, displaying resolution of 4.4 nm accuracy of 55 nm. The hardware cost of the developed system is about $20, which is significantly less than most commercial products with similar function and capability.

It is two innovational points that select the linear region and judge the location when the measured object cross the focus point by using the SS in our system. The research shows that judging has a certain deviation. In the future, we shall focus on this part in order to further improve the precision of the system.

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