

# AN AUTOFOCUSING PROBE FOR PROFILE MEASUREMENT

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*Abstract: In this research, a low cost high-precision auto-focus laser probe system was developed. Modified from the pickup head of a market available compact disc player as basis, it can detect the Focus Error Signal (FES) of the object with a built-in four-quadrant photodiode. The FES will feedback to the developed controller through which the objective lens can be adjusted to remain in focus using a voice coil motor (VCM). The driving current (converted from Servo FES) of the VCM and objective lens displacement is one to one linearly related within few hundred micrometers. Because of this relationship, the surface profile of the tested object can be realized. Experimental results showed that the designed probe has 200  $\mu\text{m}$  linearity range, 0.2 accuracy and 0.0854  $\mu\text{m}$  resolutions. Some applications are given to show the applicability of this probe system.*

*Keywords: CD Pickup Head, Auto-Focus, Voice Coil Motor, Focus Error Signal*

## 1 INTRODUCTION

Technologies of ultra-precision machining have been rapidly grown in recent years. The corresponding inspection technologies with both the resolution and accuracy achieving to submicron or even to nanometer level have also received a great attention worldwide. From precision perspective, micrometer probes are becoming less adequate, while finer measuring probes have high cost and sophistication. Hence in this research a new measuring probe was developed to have high precision capability at a low cost.

From past researches [1~4], the use of optical probe enables a non-contact measuring approach. Using optical properties, precise measurements are taken without damages to the measured object. Market available compact disk (CD) player's pickup head contains the following components: laser diode, grating, polarization beam splitter and  $\frac{1}{4}$   $\lambda$  plate, four-quadrant photodiode IC, objective lens and voice coil motor (VCM). Using advance skills to combine these components resulted in very useful properties for our research purpose.

## 2 PROBE SYSTEM

### 2.1 Pickup Head and Autofocusing Technique

The pickup head uses laser diode to produce optical light. Passing through a grating the light diffracts into three beams, as shown in Figure 1. These beams pass through a polarized beam splitter, a quarter wave plate, and an objective lens and finally focus on the measuring surface. The light is then reflected back along the original path and passes through a cylindrical lens, and finally lands on the four-quadrant photodiode, which will output a FES according to the light position in each quadrant. This focus error signal, after signal processing, is used to drive the voice coil motor. The motor shifts the objective lens until the focal point is on the object surface. The amount of VCM movement is recorded and is equivalent to the profile change of the object.

This research uses CD pickup head with reference to its service manual [5]. We know the focus theory is of the Astigmatic method. As shown in Fig. 2, when the object plane is away from the focal distance of the objective lens the light on the four-quadrant photo detector will become an elliptical shape (Plane 1, Plane 3). If object is on focus point, the light image will be in circular shape (Plane 2). Using proper signal processing we can obtain the focus error's S-Curve.

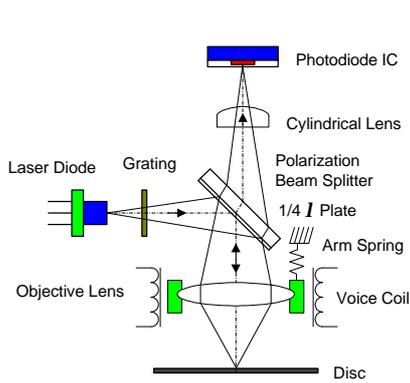


Figure 1. Laser Pickup Head's Structure

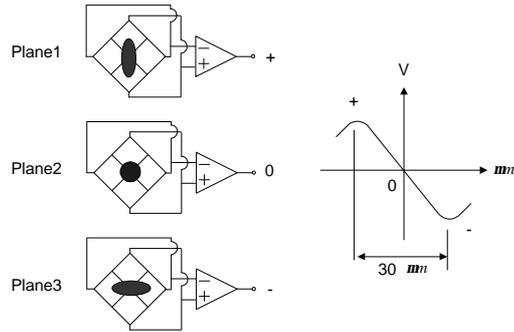


Figure 2. The variation of spot shapes with S-Curve

### 2-2 Auto-Focus Theory

As shown in Fig. 3, when the focus point is right on the reflecting surface the focus error signal will be zero. It corresponds to the middle position of the S-curve. When the object moves closer or away from the objective lens, the FES will have a non-zero output. This signal is processed and used to generate a current source to drive the VCM, which carries the objective lens so as to reduce the FES. Finally the lens stops its position when FES returns zero. The current needed to maintain the objective lens steadily will be converted to a corresponding voltage signal, which can be calibrated in terms of the actual movement of the objective lens by an HP 5528 laser interferometer. The result is given in Fig. 4 from which the linear range is found with 2,000  $\mu\text{m}$ . In practice, however, only the central range of approximately 200  $\mu\text{m}$  was adopted in use.

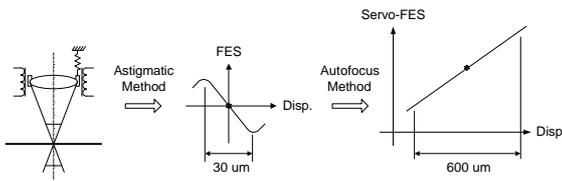


Figure 3. Servo FES relationship, focused surface

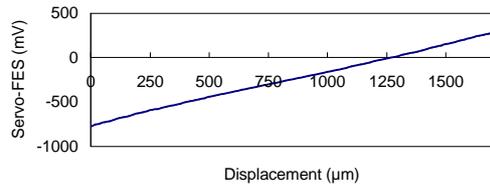


Figure 4. Relationship of the Servo FES with lens displacement

## 3 SYSTEM DESIGN AND ANALYSIS

### 3-1 Mechanical System Characteristics [6,7]

In the laser pickup head, the mechanical system not only adjusts objective lens as well as the VCM, it also provides elastic recovery force to balance with the magnetic force of the VCM. Such a system can be modeled with a second order forced vibration system, as shown in fig. 5.

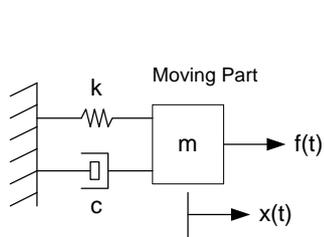


Figure 5. Mechanical model of the lens/VCM system

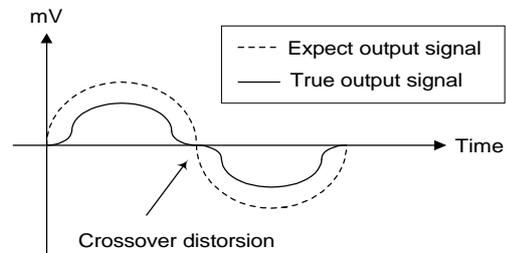


Figure 6. VCM Crossover distortion

Using Laplace transformation the mechanical system's transfer function can be expressed as:

$$\frac{X(s)}{F(s)} = \frac{1}{ms^2 + cs + k} \quad (1)$$

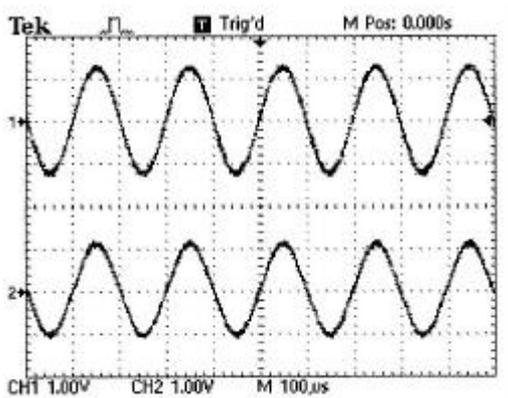
From experiments, it was found that the mass of the moving body ( $m$ ) was 1.8g, the spring constant ( $k$ ) was 26.74 (N/m), and damping coefficient ( $c$ ) was 0.07 (N·S/m). Therefore, equation (1) can be rewritten to

$$\frac{X(S)}{F(S)} = \frac{1}{0.0018S^2 + 0.07S + 26.47} \quad (2)$$

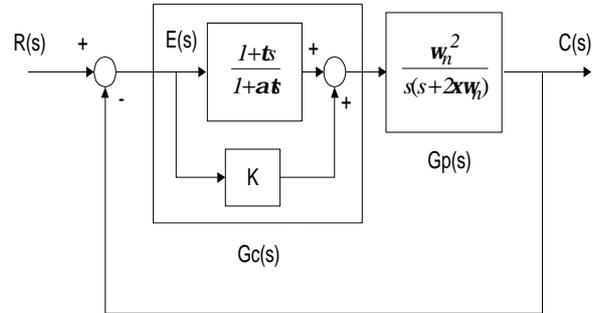
Again, with a vibration testing apparatus, the dynamic characteristics of the mechanical system were found that the natural frequency is 19.4Hz, damping ratio is 0.161 and system bandwidth is 29.56Hz. As indicated in the service manual of the pickup head [5], the natural frequency is 20 Hz, which is in good agreement with the experiment we found.

### 3-2 Actuator System Design and Analysis

In general, the output FES is very weak. Hence the FES needs to be amplified to a useable level to achieve the auto-focusing purpose. It was found from experiments, however, if just employed a simple push-pull amplifier [7], the VCM performed with crossover distortion, as shown in Fig. 6. Therefore, a compensation circuit of double push-pull circuit was developed to remove such kind of distortion. It is shown in Fig. 7 that after crossover compensation the VCM motion can follow the input signal up to 10KHz without distortion.



**Figure 7.** Results of crossover compensation, (1) command input, (2) VCM response



**Figure 8.** Compensation block diagram,  $G_c(s)$ : proportional and phase leading controller,  $G_p(s)$ : original mechanical system

In addition, in order to increase the system gain and response, two types of controllers are employed, namely the proportional controller and the phase leading controller, as shown in Fig. 8. Using frequency domain analysis the compensator's transfer function is:

$$G_c(j\omega) = \frac{(1+K) + j\omega(1+aK)t}{1+j\omega at} \quad (3)$$

The gain and the phase are:

$$Gain = |G_c(j\omega)| = \frac{\sqrt{(1+K)^2 + (1+aK)^2 t^2 \omega^2}}{\sqrt{1+a^2 t^2 \omega^2}}, \quad Phase = \angle G_c(j\omega) = \tan^{-1} \left( \frac{(1+aK)\omega t}{1+K} \right) - \tan^{-1}(\omega at)$$

We can see that the system's gain and phase values are influenced by  $K$ ,  $a$  and  $t$ . For simplicity  $t$  is calculated from circuit RC value,  $K$  is a variable, and  $a = \frac{1 - \sin f_m}{1 + \sin f_m}$  is still largely determined by  $f_m$ , the maximum phase lead. Some experiments were carried out to investigate the best values of these three parameters. It was found that to reach suitable gain and phase,  $f_m = 45^\circ$  was chosen which led to  $a$  about 0.1716,  $K=2$ , and  $t = 0.016$ . Under such conditions, in high frequency range the drop off in phase was slower, suitable for the requirement of phase leading compensation. Also the

system gain increased slowly which met the system requirements in force balance and avoiding amplified noise. The whole system diagram is shown in Fig. 9.

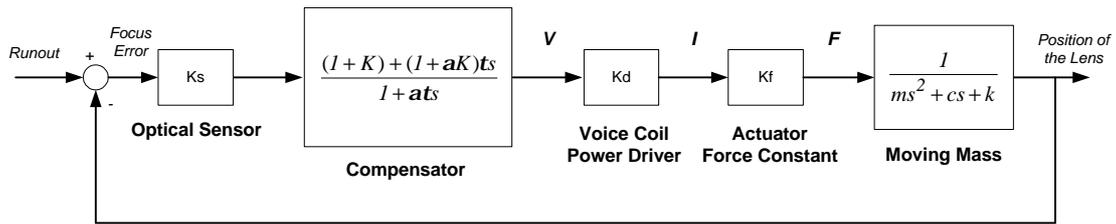


Figure 9. Servo controlled system block diagram of the pickup head

#### 4 SYSTEM CALIBRATION

Fig. 10 plots the set-up and its system diagram of the autofocusing probe for profile measurement. The object was fixed and the pickup head was driven by a micro-positioning stage, made by Parker Co. The displacement of the object was detected by an HP 5528 laser interferometer whose readout was compared with the VCM displacement of the pickup head. Previous results have shown that within the focal range the pickup head performed a very consistent linearity with respect to the particular material and its slope changes at a selected range of  $10 \mu m$  [8]. This study actuated the autofocusing function of the pickup head so that the measuring range could be extended to  $200 \mu m$ . The results are listed in Table 1, from which we can see that with 9 test runs the accuracy was about  $0.2 \mu m$  in average.

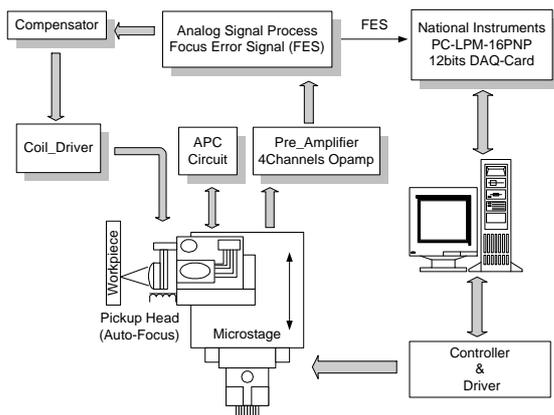


Figure 10. System setup for profile measurement

Table 1. Calibration results

| Data    | Standa<br>rd<br>Deviation* | Slope**<br>(mV/ $\mu m$ ) | Slope<br>Inverse | Error<br>***( $\mu m$ ) |
|---------|----------------------------|---------------------------|------------------|-------------------------|
| 1       | 0.1773                     | 1.2605                    | 0.793651         | 0.1407                  |
| 2       | 0.2698                     | 1.2615                    | 0.792707         | 0.2138                  |
| 3       | 0.2416                     | 1.2345                    | 0.810373         | 0.1957                  |
| 4       | 0.3057                     | 1.2403                    | 0.806257         | 0.2464                  |
| 5       | 0.2643                     | 1.2803                    | 0.781067         | 0.2064                  |
| 6       | 0.3307                     | 1.2516                    | 0.799361         | 0.2643                  |
| 7       | 0.2348                     | 1.2332                    | 0.811031         | 0.1903                  |
| 8       | 0.2308                     | 1.2409                    | 0.805867         | 0.1859                  |
| 9       | 0.2436                     | 1.2385                    | 0.807428         | 0.1967                  |
| Average | 0.2554                     | 1.2490                    | 0.80086          | 0.2045                  |

#### 5 APPLICATIONS

##### 5.1 Step Height Measurement

Two grade-one gauge blocks with nominal lengths of 1.08 mm and 1.05 mm respectively were put together on a reference plane, as shown in Fig. 11. The autofocusing probe scanned the surface across the step height. Received signals were dramatically influenced by the chamfer of each block, which reflected the light away from the sensor. The sum of light intensity accordingly dropped and hence the focus error signal (FES) jumped up. To avoid this noised phenomenon, we therefore placed two plane mirrors with the same thickness on the top of the gauge blocks, and the measured results are shown in Fig. 12. Using the least squares method, two straight lines can be fitted into two sides of surface data respectively. The distance of the offsets of these two straight lines (-198.61 and -168.35) was found about  $30.26 \mu m$ , which is very close to the nominal value of  $30 \mu m$ .

##### 5.2 Thickness Measurement of Thin Film

A glass substrate was coated with a thin film by physical vapor deposition (PVD) process. The nominal thickness was  $2 \mu m$ . Since the film and the substrate glass are made of different materials, which would respond different linearity curves, therefore recording the VCM displacements at two

different focal points with respect to different material surfaces is more appropriate in this study. Fig. 13 shows the measured profile across the coating edge. The irregular signals reflect the impurity of the coated surface. With the least squares method, we could fit two straight lines of two tested material surfaces respectively, as shown in Fig. 14. The distance of these two lines was found about 1.95  $\mu\text{m}$ , which is quite close to the nominal value.

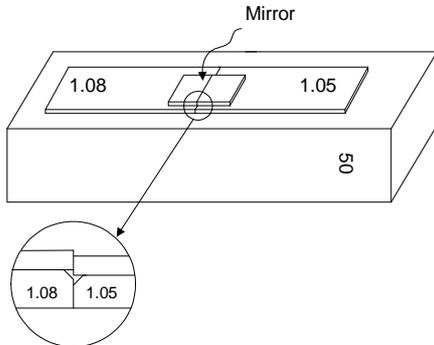


Figure 11. A step-height measurement

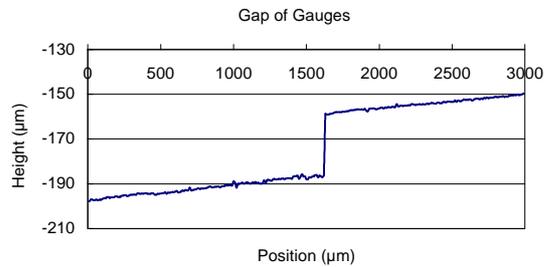


Figure 12. Results of measurement

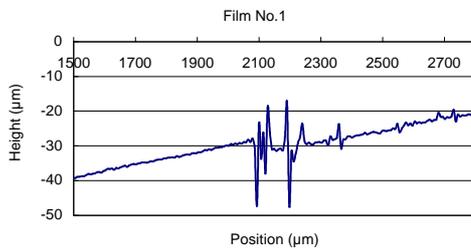


Figure 13. Measured profile of the thin film fitting

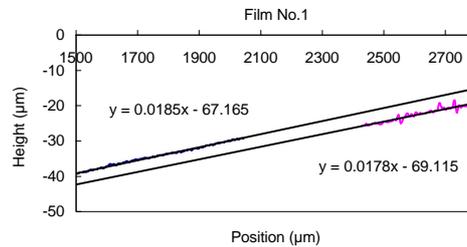


Figure 14. Extended lines after least squares fitting

## 6 CONCLUSIONS

In today's advanced manufacturing technology, market demands continuously increase product precision and reduce in physical size. To satisfy high precision measurement at non-destructive condition, optical measuring probes are very useful. In this research, a CD player's pickup head has been successfully modified to become a low cost, high precision, and auto-focusing measuring system. This system has measuring range up to 200  $\mu\text{m}$  with accuracy about 0.2  $\mu\text{m}$ , and resolution to 0.0854  $\mu\text{m}$ .

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