Dynamic Measurement of Mechanical and Optical Characteristics of Optical Disks*

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This paper describes new systems for measuring mechanical and optical characteristics of optical disks. These characteristics are necessary for designing the head actuator and standard disks for high rotational speeds. The system for measuring mechanical characteristics uses a new lens actuator with high-speed servo performance. The magneto-optic (MO) signal quality is evaluated by measuring the birefringence effects of the disk substrate. This paper also discusses disk stretch, which is important in considering data reliability at high rotational speeds.

Key Words: Laser, Sensor, Optical Engineering, Measurement, Runout, Optical Disk, Head actuator, Retardation, Refractive index ellipsoid

1. Introduction

Optical disks have a cost per data capacity ratio that is superior to that of conventional magnetic disks. They are beginning to be introduced to computer storage systems. However, the data transfer rate of optical disks is still only about half as good as that of magnetic disks. Therefore, current research and development aims to improve the transfer rate by increasing the disk rotational speed or by using multiple-beam laser diodes to record data in parallel. It seems that in the near future, higher rotational speed recording will be more promising for high data transfer rates than parallel data recording. Accordingly, mechanical and optical characteristics of optical disks must be evaluated at high rotational speeds to design the focusing and tracking servo systems which use the standard disks. This new measuring system evaluates the disk mechanical characteristics using a

new lens actuator⁽¹⁾ and a position sensor at rotational speeds up to 4 800 rpm.

The MO signal level seems to be influenced by the disk rotational speed. Birefringences of the disk substrate affect the reflected light polarization and reduce the readout signal amplitude in the MO system. Birefringences are caused by residual stress with photoelastic effects⁽²⁾⁽³⁾. To clarify the birefringence effects caused by the centrifugal force at a high-speed disk rotation, a new system of measuring optical retardation was developed. MO readout signal performances can be analyzed using these experimental results. The new measuring system can evaluate these optical characteristics at rotational speeds of up to 4 200 rpm.

2. Measuring System Design Considerations

2.1 Mechanical characteristics

Axial and radial runouts are measured by detecting movement of the focus and track actuators. Since these actuators are controlled so as to follow a track within a fixed error range in both the axial and radial directions, displacements in both directions can be measured by detecting movement of the actuators.

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Because the object disk to be measured is usually a 130 mm diameter optical disk, the measuring range in the axial direction should be more than ± 0.4 mm, and more than ± 0.05 mm in the radial direction. Sensing resolutions should be less than $1\text{ }\mu\text{m}$ and $0.1\text{ }\mu\text{m}$ in the axial and radial directions, respectively. The gain-crossover frequency for the measuring system's servo actuator must be 1.5 kHz for the present rotational speed of 1 800 rpm. Although acceleration increases quadratically with rotational speed, the following capability of the servo actuator also increases quadratically with the gain-crossover frequency. Consequently, focus and track servo actuators with gain-crossover frequencies of higher than 4 kHz must be developed for a rotational speed of 4 800 rpm.

As mentioned above, acceleration seems to quadratically increase with rotational speed, if there are no other influences on a rapidly rotating disk. Thus acceleration must also be measured when investigating the disk characteristics of each rotational speed for the recording and reading of disk data.

2.2 Optical characteristics

The polarization rotation of the reflected beam due to the Kerr effect in the recording layer can be detected by optical analyzers. The birefringence of the disk substrate causes optical retardations and changes an incident, linearly polarized beam to an elliptically polarized beam during the MO readout process. Therefore the extinction ratio of the readout beam passed through the analyzers is reduced by the ellipticity of the beam. This causes the reduction of the MO signal level.

Polycarbonate, which is used for almost all plastic disk substrates, has many mechanical and optical advantages but has the problem of birefringence. Additionally its birefringence is easily changed by the stress because of its large photoelastic coefficient. The main factors that cause stress in disk substrates are residual stress resulting from injection molding, media sputtering, and sticking processes, and a centrifugal force caused by high-speed disk rotation.

To simulate the MO signal quality, the refractive index ellipsoid of the disk substrate, which has six parameters, must be determined because the polycarbonate disk substrate has in-plane and cross-plane birefringences. The in-plane birefringence is known to be about 10^{-5} and the cross-plane birefringence about 10^{-4} . Therefore, the measurement system must have a detection resolution on the order of 10^{-6} for refractive index. These values are derived by analyzing the optical retardations of several incident angles.

Conventional refractive index measurement systems such as an ellipsometer cannot measure the birefringence of the disk substrate when it is rotating

rapidly. The new retardation measurement system was developed to evaluate optical retardations of rapidly rotating disks from eleven beam incident angles.

3. Measuring System

3.1 Mechanical characteristics

The main elements of the system for measuring mechanical characteristics are the head actuators, sensors, and the data processing systems.

Head actuator

The head actuators are relay-lens-type actuators and conventional CVM-type actuators⁽⁴⁾, with priority given to high stiffnesses and driving force efficiencies. Figure 1 shows the schematic servo operation with these head actuators.

The objective lens follows the disk axial runout by moving along the axial direction in the case of the focusing servo. Similarly, relay lens 1 follows the track radial runout by moving across the optical axis in the case of the tracking servo. The light spot focused by relay lens 1 is re-imaged on the disk with a magnitude of f_o/f_{R2} , where f_o and f_{R2} are the focal lengths of the objective lens and relay lens 2, respectively. The axial and radial runouts can be measured by detecting the movements of the objective lens and relay lens 1, respectively.

Figure 2 shows loop transfer characteristics of the focusing and tracking servos. By suppressing higher-order resonances below 20 kHz, servo gain-crossover frequencies higher than 5 kHz have been achieved using a one degree of freedom structure. This makes it possible to measure the disk runouts of standard optical disks at rotational speeds over 4 800 rpm, because the gain-crossover frequency of a conventional system's servo actuator is 1.5 kHz for a rotational speed of 1 800 rpm.

Fig. 1 Schematic servo operation

Sensors

The sensor is composed of an LED, a split photodetector, and an interrupt pin, as shown in Fig. 3. The displacement of the actuator to which the interrupt pin is connected can be measured by detecting the imbalance in the light exposure interrupted by this pin on the split photodetector.

Figure 4 shows the relationship between signal outputs and displacements of axial and radial position sensors. The linear measuring ranges in the axial and radial directions are ± 0.3 mm and ± 0.1 mm (bounded by $\pm 10\%$ errors), respectively. The nonlinear factors are easily compensated for to extend the measuring range by the processor after collecting data. The resolutions of the sensors are better than $0.1\text{ }\mu\text{m}$ in the focus direction and $0.03\text{ }\mu\text{m}$ in the track direction at a temporal response of 40 kHz.

The spindle motor of the turntable is supported by an air-pressured bearing, which reduces the runouts of the turntable to within $0.2\text{ }\mu\text{m}$ in the axial

Fig. 2 Loop transfer characteristics

Fig. 3 Construction of position sensor

direction and $0.6\text{ }\mu\text{m}$ in the radial direction. The rotational speed can be controlled from 600 to 6 000 rpm for measuring disk characteristics.

3.2 Optical characteristics

The optical characteristics measuring system consists of an optical head, signal acquisition processors, and a system controller. The signal acquisition processors are automatically controlled by a personal computer to measure data of the rotating disk automatically from 600 to 4 200 rpm.

The measuring optical head consists of the light source unit, the servo optic unit, variable aperture unit, and the polarization analyzer unit, as shown in Fig. 5. Fundamentally, this head has the same servo optic unit as the write-once-type optical head does. The variable aperture unit selects the direction of the

Fig. 4 Relationship between the detector output and the lens displacement

Fig. 5 Optical head for measuring birefringence

diagonal light beams reflected from the disk and passes the selected beam through to the polarization analyzer unit.

The incident beam from the light source unit has a precise circular polarization, and its wavelength is 830 nm. The incident beam is automatically focused and follows the recording track according to signals obtained by the servo optic unit. The variable-aperture unit chooses a specified direction from the combination of three incident beam angles of 0, 13, or 24 degrees and five incident directions of 0, 45, 90, 135, or 180 degrees of the beam cross section by moving pinholes, as shown in Fig. 6. The polarization characteristics of the selected light passed through the aperture are analyzed by four fixed optical analyzers of 0, 45, 90, and 135 degrees.

When Jones vector V of the selected light is presented by

$$V = \begin{bmatrix} E_1 \\ E_2 \end{bmatrix} \quad (1)$$

and the elliptical function of the substrate can be expressed by Jones Matrix M ,

$$M = M_1 M_2 M_3 \\ = \begin{bmatrix} \cos P & -\sin P \\ \sin P & \cos P \end{bmatrix} \begin{bmatrix} \exp\left(-j\frac{R}{2}\right) & 0 \\ 0 & \exp\left(j\frac{R}{2}\right) \end{bmatrix} \\ \times \begin{bmatrix} \cos P & \sin P \\ -\sin P & \cos P \end{bmatrix}, \quad (2)$$

where M_2 indicates a retardation R , and M_1 and M_3 indicate the direction P of the fast axis, then, V is

$$V = M V_0, \quad (3)$$

where $V_0 = \frac{1}{\sqrt{2}} \begin{bmatrix} j \\ 1 \end{bmatrix}$ is the launching circular polarized beam.

Fig. 6 Variable-aperture unit

Each analyzed beam passed through the polarizer is expressed as

$$V_i = A_i V, \quad (4)$$

where A_i is the polarizer function ($i=0, 45, 90$, and 135 degrees).

$$A_0 = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}, \quad A_{45} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -1 \\ 0 & 0 \end{bmatrix} \\ A_{90} = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}, \quad A_{135} = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & 0 \\ 1 & 1 \end{bmatrix} \quad (5)$$

and the detector output I_i is given by

$$I_i = E_{1i}^2 + E_{2i}^2. \quad (6)$$

The signal processor reads the four detector output signals through the analyzers, that is, I_0 , I_{45} , I_{90} , and I_{135} , and calculates retardation R and fast axis P using the above equations. R and P are introduced by Eqs. (2), (3), (4), (5), and (6) and are expressed as

$$R = \sin^{-1} \left(\sqrt{\left(\frac{I_{45} - I_{135}}{I_{45} + I_{135}} \right)^2 + \left(\frac{I_{90} - I_0}{I_{90} + I_0} \right)^2} \right) \quad (7)$$

$$P = \tan^{-1} \left(\frac{(I_{90} - I_0)(I_{45} + I_{135})}{2 \cdot (I_{90} + I_0)(I_{45} - I_{135})} \right)$$

The remnant fixed retardation and the absorption of the light transmittance of the optical components were calibrated by the referring test wave plates made of quartz. Then they were automatically compensated for with the signal processor.

The detection error increases as the measured retardation increases because the output of this analyzer is described by a sinusoidal function, as in Eq. (7). However, the polarization detection error is less than 3 degrees within the practical ranges where the retardation is less than 50 degrees.

4. Experimental Results

4.1 Mechanical characteristics

Figure 7 shows the experimental results of measuring axial and radial runouts of polycarbonate (PC) double-sided disks for rotational speeds from 1 800 to 4 800 rpm. Both the axial runout of $64 \mu\text{m}_0\text{-p}$ and radial runout of $22 \mu\text{m}_0\text{-p}$ of disk A at 1 800 rpm conform to the ISO standard specifications. The vibrating amplitudes of the axial runout decrease as the rotational speed increases because of the centrifugal force.

The axial and radial accelerations can be analytically evaluated from the differential of the position-sensors signal with a band-pass filter at the servo operations. The relation between the differentiated output signal and its acceleration is calibrated using a sine-wave input signal, where the lower and higher gain-crossover frequencies of the differential filter are 30 Hz and 1.5 kHz, respectively, at 1 800 rpm. Figure 8 shows an example of the axial accelerations of an optical disk against the rotational speed, where the higher gain-crossover frequencies are changed in

proportion to the rotational speed. The axial acceleration increases almost quadratically in proportion to the rotational speed and coincides with the calculated values inferred by the basic accelerations at 1800 rpm. This result indicates that there are no factors, such as flutter or vibration, that affect accelerations at high rotational speeds. The disk probably behaves as a rigid body, and the air flow around the disk surface is not turbulent at high rotational speeds such as 4800 rpm.

When the disk rotational speed starts to increase at the initial operation of the drive, the large centrifugal force stretches the disk in the radial direction. Disk stretch can be a serious problem for the track-accessing servo system if the optical scale is applied to address the referred track on the disk, because of the un-match between the original track address and the converted address mapped on the scale.

Fig. 7 Experimental results of axial and radial runouts

Fig. 8 Axial acceleration and runout of the disk

Figure 9 shows disk stretch by measuring the deviation averaged from the maximum and minimum values of runouts from the period from when the rotation started until it reached rotational speeds of 2400 and 4800 rpm.

The saturated stretch value indicates the balance of the residual stress and the strain caused by the centrifugal force as a behavior of the elastic material. The stretch saturated after several hours, and contracted when the rotating speed become lower. No damage, including microcracks, occurred in these disks at such rotational speeds. The stretch is only 1 to 2 μm at 2400 rpm, but increases to about 8 μm at 4800 rpm. Therefore, the method of direct address management and access control is suitable for rapidly rotating disks.

4.2 Optical characteristics

The normal incident light beam retardation mainly indicates the in-plane residual stress of the substrate. Figure 10 shows the relationship between the measured retardations and the disk rotational speed. The retardations decrease as the rotational speed increases at radius 30 and 40 mm, but increase at

Fig. 9 Stretch of the disk

Fig. 10 Optical retardation of the normal incident beam

Fig. 11 MO signal level degradation

radius 55 mm. This indicates that the initial residual radial stress (F_r) is larger than the tangential stress (F_t) at the radii of 30 and 40 mm. As the rotational speed increases, the tangential stress caused by centrifugal force increases, reducing the difference in residual stress between tangential and radial directions. Consequently, the retardation (R), calculated as $R = k(F_t - F_r)$, becomes small. However, at a radius of 55 mm, the initial F_r is smaller than F_t .

The refractive index ellipsoid was also derived by analyzing the retardations measured with eleven different diagonal direction beams. Once the refractive ellipsoid is evaluated, the degradation of the MO signal is calculated as shown in Fig. 11.

The calculated signal levels are normalized for the birefringence free condition, where the refractive index ellipsoid is spherical. Figure 11 shows that the MO signal level decrease caused by the centrifugal force can be estimated within 2% at rotational speeds from 600 to 4 200 rpm.

5. Conclusions

A new system for measuring the disk characteris-

tics at high rotational speeds was developed. It can measure the optical disk runouts and accelerations at rotational speeds up to 4 800 rpm. New relay lens actuators were used to achieve a high-speed following capability for its higher stiffness. Optical position sensors were used to detect the displacements with a resolution of $0.1 \mu\text{m}$ or better. The axial runout decreases with the rotational speed, and the acceleration increases almost quadratically with the rotational speed without any factors such as flutter or vibration.

The dynamic retardation measurement system using diagonal reflected beams was developed to evaluate the birefringence of disks at a high rotational speed. The refractive index ellipsoid parameters were calculated and the MO signal decrease was estimated to be less than 2% up to the rotational speed of 4 200 rpm.

Consequently, the birefringence caused by centrifugal force is considered not to have a serious effect upon the signal performance.

References

- (1) Watabe, A., Katoh, K. and Ukita, H., A High Stiffness Optical Head for Quick Access and Precise Tracking Servo., Proc. SPIE, Vol. 529 (1985), p. 150.
- (2) Treves, D. and Bloomberg, D. S., Effect of Birefringence on Optical Memory Systems, SPIE, Vol. 695 (1986), p. 262.
- (3) Watabe, A. and Hara, S., Analysis on the Magneto-Optical Signal Distorted by the Disk Substrate Birefringence, Optical Memory Symp. '86(1986), p. 27.
- (4) Yoshizawa, T. and Hara, S., The Method to Measure the Mechanical Characteristics of Optical Disk, Optical Memory Symp. '86 (1986), p. 145.