Analysis of beam spot deviation considering vibration of components in optical pickup

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Abstract

An optical disc drive uses an optical pickup to read and write data by focusing a laser beam on the data plane of a rotating disc. The pickup is required to keep the beam spot on the current track. The latest trend of replacing metal pickup housing with plastic easily excites elastic deformation modes of the pickup housing. Optical components mounted on the housing are vibrated at the mode frequencies of the housing as well. These vibrations tilt the incident angle of a laser beam entering the objective lens and results in the displacement of the beam spot on the data plane. Our purpose in this paper is to improve the accuracy of a vibration model for optical pickups by considering the effect of the elastic deformation modes of the housing in addition to the commonly used mechanical dynamics of an objective lens actuator in order to predict stability in a tracking servo system. The effect of the elastic deformation modes of the housing was formulated as the incident angle deviation and was calculated by adding and subtracting the products of a ray transfer matrix chain representing the transfer from each optical component to the objective lens with its small displacement and tilt vector. This new vibration model reproduced an increased gain around a frequency of 20 kHz in the measured open-loop transfer function of the tracking servo system with 4% error in frequency, which was entirely unexpected in the context of existing vibration models for optical pickups. The calculated results also identified the most influential vibration modes of the housing and estimated the effectiveness of stiffening the housing with 17% error.

Keywords: Vibration, Positioning, Frequency response, Ray transfer matrix method, Optical disc drive

1. Introduction

Optical discs, such as CDs, DVDs, and BDs, are most commonly used for distributing music, movies, and other data because of their removability, non-contact readability and writability, and ease of use. An optical disc drive uses an optical pickup to read and write data by focusing a laser beam on the data plane of a rotating disc. The optical pickup is required to accurately keep the beam spot on the current track and to quickly move the beam spot on the target track on the data plane. These demands require an optical pickup to have a wide servo bandwidth. It is necessary for the mechanical high-order resonances of an optical pickup to be increased in frequency to expand the servo bandwidth, especially in high-density and high-speed optical disc drives.

The bandwidth in a tracking servo system was improved by increasing the frequencies of the high-order elastic deformation modes of an objective lens actuator (Kimura et al., 2000 and Kim et al., 2009) and by arranging a coil and magnet structure to generate driving forces at the nodal points of the influential high-order elastic deformation mode of an objective lens actuator (Kajiwara and Nagamatsu, 1993, Kimura et al., 2002, and Lee et al., 2003). From servo design viewpoint, notch filters are widely used to stabilize high-order elastic deformation modes of an objective lens actuator by decreasing the open-loop gain at the frequencies of the modes so that the control input does not excite the modes (Bittani et al., 2002). Alternatively, many methods have been proposed to eliminate high-order resonance peaks by using...
a galvano- or MEMS-mirror as an actuator for the tracking servo system (Ishii et al., 2003, Shimokwa et al., 2003 and Watanabe et al., 2003). These methods are commonly used to evaluate the mechanical dynamics of an objective lens and/or mirror actuators in the tracking direction and they are assumed that any other optical components to be stationary on the pickup housing.

The latest trend of replacing metals with injection molded plastics in the housing (Hashimoto et al., 2012 and Ochi et al., 2013) makes elastic deformation modes of the housing easily excited by reaction forces due to actuation of the objective lens because of the housing’s light weight and low elastic modulus. Optical components mounted on the housing are vibrated at the mode frequencies of the housing as well. This vibration also displaces the position of the beam spot focused by the objective lens. It is simple to evaluate the mechanical dynamics of the objective lens actuator when the housing is made of metals or the optical pickup does not support high speed operations, but replacing a metal pickup housing with plastics and supporting high speed operations require considering the effects of the displacement and tilt of the optical components amplified at the elastic deformation mode frequencies of the housing by reaction forces due to actuation of the objective lens.

We improved the accuracy of a vibration model for optical pickups by considering not only the commonly used mechanical dynamics of an objective lens actuator but also the effect of the elastic deformation modes of the housing. The effect of the elastic deformation modes of the housing was formalized as the incident angle deviation and was calculated by adding and subtracting the products of a ray transfer matrix chain representing the transfer from each optical component to the objective lens with its small displacement and tilt vector.

We show comparison results of calculated and measured frequency characteristics of a developed optical pickup and the validity of our proposed vibration model. This proposed vibration model is a large contribution to shortening development period of optical pickups by adding pre-evaluable item concerning stability in a tracking servo system.

2. Configuration of optical pickup

Figure 1 shows an optical pickup with resin housing for a slim super multi drive, which can read and write DVDs and CDs. The optical pickup includes a laser diode, photodetector, objective lens, and all the necessary optical components. It also uses an objective lens actuator to move the objective lens in the focusing and tracking directions. They are mounted on the optical pickup housing. The focusing direction is the Z-axis direction along the optical axis of the objective lens, and the tracking direction is the Y-axis direction in this figure. The direction perpendicular to both the Z- and Y-directions is then set to be the X-axis direction, also referred to as the tangential direction.

Figure 2 shows the optical components of the optical pickup. A laser diode, beam splitter, collimator lens, mirror, and objective lens are mounted in the optical path up to the data plane of a disc. A laser diode with light wavelengths of 780 and 650 nm is used. A divergent laser beam from the laser diode is bent by the beam splitter tilted at an angle of 45 degrees from the Z-X plane to the collimator lens. The collimator lens makes the divergent laser beam parallel. The parallel laser beam is then bent upward by the mirror tilted at an angle of 45 degrees from the X-Y plane, and it enters the objective lens. After passing through the lens, the laser beam is focused on the data plane of the disc.

Figure 3 shows the configuration of the objective lens actuator. It also shows driving and reaction forces generated on the tracking coils and magnets in the tracking direction. The actuator electromagnetically moves the objective lens in the optical path. A holder attached with an objective lens, two focusing coils, and four tracking coils is suspended between two pairs of magnets by six wires. The two pairs of magnets are attached to a yoke, and the yoke is fixed on the housing. A current applied to the coils generates driving forces on the coils to move the objective lens and the beam spot on the data plane in the focusing and tracking directions. This movement keeps the beam spot on the target track on the date plane of the rotating disc. This current applied to the coils generates reaction forces on the magnets at the same time, and the reaction forces excite the elastic deformation modes of the housing.
Fig. 1 Optical pickup with resin housing for slim optical disc drive. Height, width, and distance between bearings of optical pickup are about 5, 35, and 45 mm, respectively.

Fig. 2 Configuration of optical system. Red-colored shape indicates propagation of laser beams emitted from laser diode to data plane of disc and reflected from data plane onto photodetector. It is noted that only external shape of pickup housing is transparent, and optical disc is illustrated as partially cut away.
3. Causes of beam spot deviation on data plane

A vibration model for an optical pickup is commonly substituted with the mechanical dynamics of an objective lens actuator using a frequency response function, which is represented as the ratio of the displacement of the objective lens to the current applied to the coils (Kim et al., 2011 and Cherubini et. al., 2012), referred to as $H_A(f)$. Figure 4(a) plots the measured frequency response function regarding the displacement of the objective lens in the tracking direction. First-order resonance, which is a bending mode of the suspension wires, occurs at about 70 Hz, while several high-order resonances, which are elastic deformation modes of the holder, occur above 40 kHz. The lowest high-order resonance frequency limits the increase in servo bandwidth. Provided the servo bandwidth is set to be 5 kHz, any resonance frequencies must not exist near the phase crossover frequency around 20 kHz for the servo system to be stable. Figure 4(b) plots a magnified view of the frequency range from 15 to 25 kHz in Fig. 4(a). A frequency characteristic is observed as a smooth line without any peaks in this area. Hence, a mass-spring-damper model is applicable for $H_A(f)$ in the 15 to 25 kHz frequency range, and it follows that

$$H_A(f) = -\frac{a}{(2\pi f)^2}$$

where $f$ represents the frequency in a range from 15 to 25 kHz, and $a$ is the acceleration sensitivity, that is, the output acceleration change per unit of input current applied to the tracking coils.

Meanwhile, Fig. 5 plots a measured open-loop transfer function of the tracking servo system by using an evaluation unit. The gain and phase crossover frequencies were set at 3.5 and 7.5 kHz, respectively. They are much lower than those of an actual optical disc drive. This difference in setting changes the vertical location of the gain graph but does not change its shape and size.

The gain increases around a frequency of 20 kHz, though the objective lens actuator does not have any peaks in the area as shown in Fig. 4(b). This increase in gain is no longer explained only by the conventionally used mechanical dynamics of an objective lens actuator. The beam spot position on the data plane is also displaced by the incident angle deviation of the laser beam onto the objective lens as shown in Fig. 6. The incident angle is made to deviate by the displacement and tilt of the optical components mounted on the housing, though this effect was neglected in other models previously, so that the effect of this incident angle deviation of the laser beam onto the objective lens caused by reaction
forces due to actuation of the objective lens should be added to the above vibration model, especially when the housing is made of injection molded plastics.

A newly employed vibration model of an optical pickup, $H(f)$, is then defined as

$$H(f) = H_A(f) + H_O(f)$$

(2)

where $H(f)$ is represented as a sum of frequency response functions $H_A(f)$ and $H_O(f)$. $H_O(f)$ is obtained by first multiplying the focal length of the objective lens and the incident angle deviation of the laser beam onto the objective lens and then dividing by the current applied to the tracking coils. Within the limit of paraxial ray approximation, $H_O(f)$ is expressed as

$$H_O(f) = F_O \theta_O(f)$$

(3)

where $F_O$ is the focal length of the objective lens, and $\theta_O(f)$ is the incident angle deviation of the laser beam onto the objective lens per unit of input current applied to the tracking coils. In this paper, $\theta_O(f)$ is formulated by using a matrix method. This is discussed separately in the following section.

Fig. 4 Measured frequency response of displacement of objective lens in tracking direction. (a) In entire measured frequency region. First-order resonance occurs at about 70 Hz, and several high-order resonances occur above 40 kHz. (b) In range from 15 to 25 kHz. Frequency characteristic is observed as smooth line without any peaks in this region.
(a) In entire measured frequency region

(b) In range from 14 to 24 kHz

Fig. 5 Measured open-loop frequency response of tracking servo system. Deep blue and deep pink curves indicate gain (left axis) and phase (right axis), respectively. Figure 5(a) plots in entire measured frequency region. Figure 5(b) plots magnified view of frequency range from 14 to 24 kHz in Fig. 5(a). Gain increases around frequency of 20 kHz.

4. Formulation of incident angle deviation of laser beam onto objective lens

We use ray transfer matrix method in order to formulate the relationship between the incident angle deviation of the laser beam onto the objective lens and displacement and tilt of the optical components.

Figure 7 schematically illustrates the optical path up to the data plane. This path includes five optical components and a disc separated by five air gaps. We locate a set of successive local coordinate systems rotated by −45 degrees each at the points of incidence on the reflecting surfaces, as shown in Fig. 7. Figure 7 also shows their parameters; $F_C$ is the focal length of the collimator lens, $d$ is the distance from the laser diode to the beam splitter, and $L_1$ and $L_2$ are the distances from the collimator lens to the mirror and from the mirror to the objective lens, respectively.

We shall only consider the $y_1$-displacement $\delta_0$ of the laser diode, the tilt $\delta'_0$ around the $x_2$-axis of the beam splitter, the $y_3$-displacement $\delta_1$ of the collimator lens, and the tilt $\delta'_1$ around the $x_3$-axis of the mirror for calculating the incident angle deviation of laser beam onto objective lens. To associate each of these displacements and tilts with the incident angle deviation of laser beam onto objective lens, we introduce the ray transfer matrix $A_j$ and small displacement and tilt vector $\delta_j$ regarding the $j$th optical component in each $y_j$-$z_j$ plane. All ray transfer matrices are summarized in Table 1.
Fig. 7 Schematic diagram of optical path up to data plane. Here, $F_O$ and $F_C$ are focal lengths of objective lens and collimator lens, respectively. $L_1$, $L_2$, and $d$ are distances from collimator lens to mirror, from mirror to objective lens, and from laser diode to beam splitter, respectively.

Table 1 List of ray transfer matrices representing optical components between laser diode and objective lens. Each matrix connects distance and angle from $z_k$-axis of input laser beam with corresponding output quantities in each $y_k$-$z_k$ plane. Provided that $A_0$ and $A_8$ are defined as zero and identify matrices, respectively. It is noted that the refractive indexes, curvature radiuses, and gap values must be sign-changed each time the laser beam is folded (Gerrard and Burch, 1975).

<table>
<thead>
<tr>
<th>Number ($j$)</th>
<th>Optical component</th>
<th>Ray transfer matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Input reference plane</td>
<td>$\begin{bmatrix} 0 &amp; 0 \ 0 &amp; 0 \end{bmatrix}$</td>
</tr>
<tr>
<td>1</td>
<td>Air gap</td>
<td>$\begin{bmatrix} 1 &amp; d \ 0 &amp; 1 \end{bmatrix}$</td>
</tr>
<tr>
<td>2</td>
<td>Beam splitter</td>
<td>$\begin{bmatrix} 1 &amp; 0 \ 0 &amp; -1 \end{bmatrix}$</td>
</tr>
<tr>
<td>3</td>
<td>Air gap</td>
<td>$\begin{bmatrix} 1 &amp; -(F_C - d) \ 0 &amp; 1 \end{bmatrix}$</td>
</tr>
<tr>
<td>4</td>
<td>Collimator lens</td>
<td>$\begin{bmatrix} 1 &amp; 0 \ 1/F_C &amp; 1 \end{bmatrix}$</td>
</tr>
<tr>
<td>5</td>
<td>Air gap</td>
<td>$\begin{bmatrix} 1 &amp; -L_1 \ 0 &amp; 1 \end{bmatrix}$</td>
</tr>
<tr>
<td>6</td>
<td>Mirror</td>
<td>$\begin{bmatrix} 1 &amp; 0 \ 0 &amp; -1 \end{bmatrix}$</td>
</tr>
<tr>
<td>7</td>
<td>Air gap</td>
<td>$\begin{bmatrix} 1 &amp; L_2 \ 0 &amp; 1 \end{bmatrix}$</td>
</tr>
<tr>
<td>8</td>
<td>Output reference plane</td>
<td>$\begin{bmatrix} 1 &amp; 0 \ 0 &amp; 1 \end{bmatrix}$</td>
</tr>
</tbody>
</table>
Using paraxial approximation, the incident angle deviation of laser beam onto objective lens $\theta_{0}(f)$ can be given as the second component of the output polar vector calculated by adding and subtracting the products of a ray transfer matrix chain representing the transfer from each optical component to the objective lens with its small displacement and tilt vector (Ochi et al., 2008).

$$
\theta_{0}(f) = [0 \ 1] \sum_{l=0}^{7} \prod_{j=1}^{8} A_{l}(I - A_{j}) \delta_{l}
$$

(4)

where $I$ is a $2 \times 2$ identify matrix, $\delta_{l} = [\delta_{l} \ \delta_{l}']^{T}$, $\delta$ and $\delta'$ are displacement and tilt of the $l$th optical component. We thus obtain the following.

$$
\theta_{0}(f) = 2\delta_{0}' \cos \varphi + \frac{1}{F_{c}} \delta_{4} - \frac{2d}{F_{c}} \delta_{2}' - \frac{1}{F_{c}} \delta_{0}
$$

(5)

It must be noted that the tilt $\delta_{0}'$ of the mirror should be reduced by the cosine for the angle $\varphi$ between the incident laser beam and the $z_{4}$-axis, because the tilt $\delta_{0}'$ of the mirror affects only the projected component of the incident unit vector on the $y_{4}$-$z_{4}$ plane. The complex-valued displacement and tilt of the optical components were computed by modal frequency response analysis with ADVENTURECluster (Suzuki et al., 2002) and substituted into Eq. (5). Modal frequency analysis was performed considering 300 modes in the frequency range of 1 Hz to 50 kHz and a modal damping ratio of 0.02, under a free-free boundary condition.

5. Results

Figure 8 plots the calculated frequency response of the displacement of the beam spot on the data plane in the tracking direction on the same scale as in Fig. 5. The calculated magnitude and phase vertically shifted from the measured ones shown in Fig. 5 due to the calculation ignoring the effects of amplifiers, lead-lag compensators, and computational time delay in the servo system. The calculated results reproduced the fluctuations around a frequency of 20 kHz in the measured results by considering effect of elastic deformation modes of the housing. There were two modes of the housing at frequencies of 19.7 and 21.6 kHz and they are integrated into one primary peak in the calculated magnitude. The differences in resonance frequencies between calculated and measured results were 1% and 4% in frequency, respectively. In consequence, the calculated resonant peaks were spaced 1.6 times farther apart than measured result. It is likely to be due to the effect of the orientation distribution of short fibers in the housing, because the housing partially deforms in high frequency range. With regard to the phase change, one mode at a frequency of 19.7 kHz has a phase opposite to the first-order resonance of the objective lens actuator and the other at a frequency of 21.6 kHz is in-phase with it. This means that calculated result agrees with measured result in the order of the vibration modes. These were entirely unexpected in the context of the conventional vibration model for an optical pickup shown in Fig. 4(b).

Figures 9 and 10 show the calculated mode shapes of the resonance frequencies of 19.7 and 21.6 kHz. The region under the mirror of the housing partially twisted and the mirror tilted along with the motion of the housing for both modes. The maximum value of the average of the strain energy density were also shown there. These calculated results raise the possibility that stiffening the housing around the mirror is effective for the purpose of decreasing the displacement of the beam spot on the data plane. The effect of stiffening the housing around the mirror was then evaluated in order to confirm the validity of this proposed vibration model of the optical pickup.

Figure 11 plots the calculated frequency responses of the displacement of the beam spot on the data plane in the tracking direction before and after stiffening the housing. There remains several peaks, but the calculated results lead to
the expectation that stiffening the housing around the mirror can reduce the displacement of the beam spot on the data plane by an estimated 5.2 dB.

Figure 12 plots a measured open-loop transfer function of the tracking servo system after stiffening the housing. Figure 12(b) plots a magnified view of the frequency range from 15 to 25 kHz in Fig. 12(a). These results were consistent with the expectation shown in Fig. 11 and proved that the primary peak resulted from the identified two elastic deformation modes of the housing.

Figure 13 shows comparison of the measured open-loop transfer functions of the tracking servo system before and after stiffening the housing in order to validate the calculated results. It was observed that the primary resonance peak was reduced by 6.8 dB. There was then difference in gain reduction of 17% between calculated and measured results. One of the possible causes is that only a constant modal damping ratio was used in modal frequency analysis regardless damping performance of adhesives bonding all components with the housing. It is also possible that the stiffness around the mirror of the housing increased not merely with the increase in thickness but with change in the flow state of resin and short fibers accompanied by the increase in thickness. Nevertheless, these results were consistent with the expectation shown in Fig. 11 and prove the effect of stiffening the housing around the mirror. In summary, our new vibration model for optical pickups can identify a main occurrence factor of destabilization in the tracking servo system, which existing vibration models may overlook, and can provide guidance toward a solution.

![Graphical representation of calculated and measured frequency responses.](image1)

(a) Calculated frequency response  
(b) Measured open-loop frequency response (Identical Fig. 5)

Fig. 8 Calculated frequency response of displacement of beam spot on data plane in tracking direction. Deep blue and deep pink curves indicate magnitude (left axis) and phase (right axis), respectively. Both magnitude and phase are same scale as in Fig. 5.

![Graphical representation of vibration mode shape.](image2)

(a) Perspective view  
(b) Bottom view

Fig. 9 Calculated vibration mode shape at resonance frequency of 19.7 kHz. Contour displays distribution of average strain energy density in pickup housing. Housing partially twisted and mirror tilted along with it. In addition, region under mirror shows maximum value of strain energy density.
Fig. 10 Calculated vibration mode shape at resonance frequency of 21.6 kHz. Contour displays distribution of average strain energy density in pickup housing. Housing partially deforms and mirror tilts similarly at resonance frequency of 19.7 kHz, but in opposite direction.

Fig. 11 Comparison of calculated frequency responses of displacement of beam spot on data plane in tracking direction before and after stiffening housing. Sky blue and deep blue curves indicate magnitudes with and without stiffened housing, respectively. Maximum value of magnitude peak around frequency of 20 kHz is expected to be reduced by 5.2 dB with stiffened housing.

Fig. 12 Measured open-loop frequency response of tracking servo system after stiffening housing. Sky blue and pink curves indicate gain (left axis) and phase (right axis), respectively. Figure 12(a) plots in entire measured frequency region. Figure 12(b) plots magnified view of frequency range from 15 to 25 kHz in Fig. 12(a). Stiffening housing decreased gain at peak frequencies around 20 kHz.
Fig. 13 Comparison of measured open-loop transfer functions of tracking servo system before and after stiffening housing. Sky blue and deep blue curves indicate gains with and without stiffened housing, respectively. Maximum value of gain peak around frequency of 20 kHz can be reduced by 6.8 dB with stiffened housing.

6. Conclusion

The following results were obtained. A new vibration model for an optical pickup was proposed by considering not only the commonly used mechanical dynamics of an objective lens actuator but also the effect of the elastic deformation modes of the housing. The effect of the elastic deformation modes of the housing was formularized as the incident angle deviation and was calculated by adding and subtracting the products of a ray transfer matrix chain representing the transfer from each optical component to the objective lens with its small displacement and tilt vector.

The new vibration model reproduced an increased gain around a frequency of 20 kHz in the open-loop transfer function of the tracking servo system with 4% error in frequency and identified the most influential vibration modes of the housing. This is entirely unexpected in the context of existing vibration models for optical pickups. The calculated results also estimated the effectiveness of stiffening the housing around the mirror with 17% error. These results therefore suggest that the new vibration model for optical pickups is useful in predicting stability in a tracking servo system, identifying a main occurrence factor of destabilization, and providing guidance toward a solution.

On the other hand, this vibration model is not enough to predict quantitatively the stability in a servo system without prototype verification. In addition, change in the mechanical characteristics with individual variations makes it difficult to predict peak frequencies and peak gains of mechanical resonances with high degrees of accuracy. Further work is also required to acquire a precise mechanical model in consideration of individual variations.

References


