A piezoelectric actuator with a motion-decoupling amplifier for optical disk drives

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Abstract
In this paper, an optical pick-up actuator is studied using a multilayered PZT (lead–zirconate–titanate) for possible application to slim and small-form-factor optical disk drives or mobile devices. A theoretical modeling and analysis of the PZT actuator including the dynamics of piezoelectric, electrode and substrate layers are performed to estimate the dynamic properties such as natural frequencies, resultant forces and maximum displacements. In particular, we suggest a novel stroke-amplifying structure enabling the decoupled tracking and focusing motions actuated by four parallel multimorphs. A flexure hinge mechanism is used as the displacement amplifier to extend the allowable stroke of the actuator. Experimental results using a cantilever actuator agree well with the analytical predictions. Based on the theoretical and experimental investigations, we have designed the final model of the optical pick-up actuator with a height of 2.5 mm, showing that the moving range is ±400 μm at 15 V in the focusing direction, which is appropriate for slim or small-form-factor optical disk drives.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Optical data recording devices have been widely used, emerging with the advent of information technologies. Trends in optical disk drives include the development of small-form-factor (SFF) drives for mobile devices and the extension of BD (blue-ray disk) drives in the storage market. The demand for slim-type optical drives has been dramatically increased for ultra-slim notebooks. Various SFF optical storages have also been released in commercial markets for mobile information devices such as mobile phones, PDAs and MP3 players. The size reduction in both slim-type and SFF devices has been one of the critical issues to overcome recently.

Hence, various types of optical pick-up actuators are proposed for slim or small-form-factor optical disk drives and camera phones. There are two approaches to reduce the size of optical pick-ups. One is to scale down all components of a conventional pick-up [1, 2]. The other approach is to combine an integrated optical pick-up with a swing arm actuator [3–5]. In optical disk drives, most of the optical pick-ups actuators are mainly based on the conventional voice coil motor (VCM). A four-wire suspension-type actuator is most commonly used in optical disk drives. Figure 1(a) shows the configuration of a four-wire suspension supporting the moving parts which include the lens holder, objective lens and coils. The moving part is actuated by the VCM to move the objective lens in focusing and tracking directions independently. Thus it is required that the optical pick-up actuators ensure the decoupling between the focusing and tracking motions to avoid unwanted motions. Unlike the VCM-based actuators, lens actuators using piezoelectric materials and optical pick-ups driven by piezoelectric actuators are also proposed [6, 7]. Even though piezoelectric actuators with proper design can satisfy the size requirement for small-form-factor devices, the moving range of piezoelectric actuators attaining the two decoupled motions still remains unsolved.
A number of researchers have studied the dynamic analysis of multilayered piezoelectric structures. Devoe and Pisano [8] investigated the piezoelectric beam model that described the deflection of a generic multilayer piezoelectric multimorph. In order to derive a simple working equation for the bending of a piezoelectric multimorph, a simple closed form solution method based on Euler–Bernoulli beam theory instead of in the longitudinal direction to cause synchronistic deformation of all layers [10]. Krommer [11] developed the constitutive equations of a multimorph by assuming two-dimensional kinematics of the structure. Besides the theory of elasticity, Ha and Kim [12] investigated the dynamic behavior of PZT actuators by using the impedance and admittance method. Also Tamor and Kosa [13] extended the Weinberg analysis to materials with arbitrary electromechanical coupling coefficients by accounting for the variation of electric field in the beam layers.

Piezoelectric materials show fast response speed, easy miniaturization and good dynamic performance. However, the low resultant force and displacement would prevent various applications. Thus, it is difficult to directly apply this method to the actuation of the optical pick-up module in optical disk drives and mobile devices. A multilayered actuator enables it to overcome the inherent limitations of the unimorph piezoelectric actuator. For this reason, it is important to perform a study on the optimization of unimorphs, bimorphs and multimorphs to maximize the tip stroke or vertical displacement using the thickness ratio between the substrate and piezoelectric layers. Li et al [14] investigated the effect of the thickness ratio on the tip stroke for unimorphs only. They showed that there exists an optimal thickness ratio for the simply supported unimorph beam. Ha and Kim [12] showed that there exists an optimal thickness ratio of the middle structure (or shim layer) thickness to the total thickness. Lee et al [15] have performed a study on the optimal number and thickness ratio of piezoelectric and structural layers consisting of a multimorph for maximizing the tip deflection and the resultant force of the tip.

In this paper, we propose a small-size pick-up actuator using a multilayered bimorph PZT (lead–zirconate–titanate) for application in slim and SFF optical disk drives, as shown in figure 1(b). A novel flexure hinge mechanism is designed as a displacement amplifier to extend the allowable stroke in both tracking and focusing motions of an optical pick-up for SFF devices. The proposed structure also exhibits decoupled motions in the focusing and tracking directions. A theoretical model, including the dynamics of multilayer PZT, is derived and it is analytically solved to predict the natural frequency and the resultant force and displacement of the PZT actuator. Experimental results agree well with the analytical predictions, showing that the proposed actuator model meets the requirements for the maximum stroke and dynamic characteristics of slim or SFF drives. Finally, based on the theoretical analysis and the preliminary experiments, we verify the validity and feasibility of the prototype model manufactured by exploiting the PZT actuator and displacement amplifier through experiments.

2. Modeling of the multilayered PZT actuator

2.1. Static analysis

In general, piezoelectric single unimorph and bimorph actuators enable large displacements. However, the low output forces and natural frequencies limit their applications to optical pick-up actuators. When a piezoelectric actuator consists of several bimorph layers, it can enlarge both the generative force and the resonance frequency, even though the applied voltage and manufacturing cost are increased. This study uses the multilayered bimorph PZT as a slim optical pick-up actuator. In general, design variables associated with the multilayered PZT actuator should be properly selected for optimal performance [10]. Thus, we consider the theoretical modeling and analysis for the development of the multilayered bimorph PZT actuator.

A bimorph PZT actuator is bonded to the top and bottom surfaces of the structures and it is driven by voltages of the opposite polarity. Therefore, when one layer is expanding, the other is contracting. This is because, even if modern piezoelectric actuators are designed to maximize the transfer of energy and thus tend to have large electromechanical coupling coefficients [16], the effect of coupling is not significant for a symmetric multimorph [13]. Therefore, the effects of lateral structural contraction counteracting the expansion of the PZT layers were neglected in this work. As shown in figure 2, the electrode and substrate layers exist between two adjacent PZT
layers. Usually a multilayered bimorph PZT has a symmetry structure in the x direction. We suppose that the total thickness of the PZT actuator is small enough for slender beam analysis where only the strain \( \varepsilon_{\text{PZT}} \) in the x direction exists. Here, we make the following assumptions:

(a) the plate thickness is much less than the radius of curvature induced by the electrical loading,
(b) the cross section of the layers is constant along the length of the plate,
(c) the \( xz \) plane is the plane of symmetry,
(d) the \( xy \) plane is the neutral surface,
(e) plane sections remain as the same plane,
(f) equilibrium requires that the resultant of the stress distribution over the cross section of the beam should equal the bending moment.

Also we assume that the stacked beam is perfectly bonded so that the linear motion is generated at the interface \([ 17]\). Then we can apply the conventional assumptions on stress and strain distributions to the static analysis. In a proposed bimorph actuator, the PZT layer is bonded to the top and bottom surfaces of the central metal electrode and it is driven by a voltage of the opposite polarity for a parallel type. A general \( n \)-layer bimorph actuator is shown in figure 2. When the electric field is applied on each electrode, PZT layers above the x axis go through extensions and the layers on the bottom side go through contractions. The location at \( x = 0 \) is fixed and the right end of the beam is free. As a result of the strain in each PZT layer, the multilayered bimorph actuator bends in its transverse direction. With reference to a previously published paper \([15]\), we can obtain the resultant tip displacement of the PZT bimorph actuators due to applied voltage, \( \delta \), as follows:

\[
\delta = \frac{3}{2} \kappa L^2,
\]

where

\[
\kappa = \left\{ d_{31} E_{\text{PZT}} V_{\text{in}} \sum_{k=1}^{N} \left( k + \frac{\beta - 1}{2} \right) \right\} \times \left[ h^2 \left\{ E_{\text{PZT}} \sum_{k=1}^{N} \left( \left( \frac{1 - \beta}{12} \right)^3 + (1 - \beta) \left( k + \frac{\beta - 1}{2} \right)^2 \right) \right] + E_{\text{struc}} \sum_{k=1}^{N} \left( \beta^3 \frac{1}{12} + \beta \left( k - 1 + \frac{\beta}{2} \right)^2 \right) \right]^{-1}.
\]

Here \( L \) and \( V_{\text{in}} \) are the free length of the bimorph and a time-varying input voltage, respectively. We define \( \beta \) as the ratio of the structure thickness, \( t_{\text{struc}} \), to the combinational thickness, \( h = t_{\text{PZT}} + t_{\text{struc}} \), where \( t_{\text{PZT}} \) is the PZT thickness. Then, \( (1 - \beta) \) represents the ratio of the PZT thickness to the combinational thickness. \( E_{\text{struc}} \) and \( E_{\text{PZT}} \) are the Young’s moduli corresponding to the structural and PZT layers. \( d_{31} \) is the transverse-piezoelectric coupling coefficient. \( 2N \) is the number of piezoelectric layers. From equation (1), we can get a resultant tip force at each quasi-equilibrium state such as

\[
P = \frac{3E I_{\text{total}} \delta}{L^3},
\]

where \( E I_{\text{total}} \) denotes the total stiffness of the multimorph including PZT and structures and is expressed as

\[
E I_{\text{total}} = \sum_{k=1}^{N} \left[ E_{\text{PZT}} (l_{\text{PZT}} + l_{\text{struc}})^2 \right] + \sum_{k=1}^{N} E_{\text{struc}} (l_{\text{struc}} + l_{\text{struc}})^2.
\]

Figure 2. Configuration of a symmetric cantilevered multimorph.
\[
E_{PZT} = h \sum_{k=1}^{N} \left( \left( \frac{1}{12} - \beta \right)^3 + 1 - \beta \left( k + \frac{\beta - 1}{2} \right)^2 \right) + E_{\text{struc}} \sum_{k=1}^{N} \left( \frac{\beta^3}{12} + \beta \left( k - 1 + \frac{\beta}{2} \right)^2 \right).
\]

Here \( E_{PZT} \) and \( E_{\text{struc}} \) represent the moments of inertia of the PZT layer and structure based on their own neutral axes, and \( z_{k, \text{PZT}} \) and \( z_{k, \text{struc}} \) denote the distances from the global neutral surface to their own neutral axes.

### 2.2. Dynamic Analysis

For analytically understanding the dynamic properties of the multimorph actuator, we carried out the dynamic analysis with respect to the PZT model. However, it is known that the PZT actuator has an aperiodic nonlinear property in general. Thus, we approximate the motion of a beam including the PZT actuator using an Euler beam model. Also, the mathematical modeling of a cantilever beam is considered. The equation of motion for a cantilever beam can be represented as follows:

\[
m \frac{\partial^2 w(x, t)}{\partial t^2} + \frac{\partial^2}{\partial x^2} \left( EI \frac{\partial^2 w(x, t)}{\partial x^2} \right) = \frac{\partial^2 M(x)_{\text{PZT}}}{\partial x^2},
\]

where \( M_{\text{PZT}} \) is a linear moment due to control input and \( m' \) is mass per unit length of a beam. The bending moment \( M_{\text{PZT}} \) is obtained from

\[
M_{\text{PZT}}(x) = M_0 \left[ H(x - x_a) - H(x - x_b) \right],
\]

where there exists only the PZT material in the region between \( x_a \) and \( x_b \). \( M_{\text{PZT}}(x) \) is the resultant moment corresponding to the region which the PZT layer covers. In this work, the PZT layer covers the entire structure of the multimorph actuator. \( H(x) \) denotes the Heaviside step function. The Heaviside step function is defined as follows:

\[
H(x) = \begin{cases} 
0 & \text{for } x < 0 \\
1 & \text{for } x > 0.
\end{cases}
\]

To solve the general equation (3), we represent the right-hand side of equation (3) with (4) as follows:

\[
\frac{d^2 M_{\text{PZT}}(x)}{dx^2} = M_0 \frac{d^2}{dx^2} \left[ H(x - x_a) - H(x - x_b) \right]
\]

\[
= M_0 \left[ \delta'(x - x_a) - \delta'(x - x_b) \right],
\]

where \( \delta' \) is the unit doublet function:

\[
M_0 = \left[ d_{31} E_{\text{PZT}} \sum_{k=1}^{N} \left( k + \frac{\beta - 1}{2} \right) \right] \times E_{\text{struc}} \sum_{k=1}^{N} \left( \frac{\beta^3}{12} + \beta \left( k - 1 + \frac{\beta}{2} \right)^2 \right),
\]

\[
\times \left[ \left( \frac{1}{12} - \beta \right)^3 + 1 - \beta \left( k + \frac{\beta - 1}{2} \right)^2 \right] + E_{\text{struc}} \sum_{k=1}^{N} \left( \frac{\beta^3}{12} + \beta \left( k - 1 + \frac{\beta}{2} \right)^2 \right) \right],
\]

After forced response analysis of a cantilever Euler beam by oscillating the voltage applied to the actuator, we get the following response:

\[
w(x, t) = \sum_{n=1}^{\infty} F_n(t) \phi_n(x).
\]

Assuming the harmonic motion and applying the boundary conditions, the associated eigenfunctions can be expressed corresponding to individual eigenvalues as follows:

\[
\phi_n(x) = \frac{A_n}{\sin \beta_n L - \sin \beta_n x} \sin \beta_n x,
\]

where \( A_n = \frac{C_n}{\sin \beta_n L - \sin \beta_n x} \). Then equation (3) may be given by

\[
\phi_n(x) \frac{d^2}{dt^2} F_n(t) + \frac{E I d^4}{m'} \phi_n(x) F_n(t)
\]

\[
= M_0 \left[ \delta'(x - x_a) - \delta'(x - x_b) \right].
\]

Using the property of normalized mode shapes and the orthogonality of the natural modes with \( V_n = V_n e^{i\omega t} \) and \( F_n(t) = F_n e^{i\omega t} \), equation (8) is represented as

\[
F_n(-w^2 + \lambda_n^2)e^{i\omega t} = -\frac{M_c A_n}{m} \left[ \phi_n'(x_a) + \phi_n'(x_b) \right] V_n e^{i\omega t}
\]

where \( M_c \) is a constant having the properties of the multimorph given as

\[
M_c = \left[ d_{31} E_{\text{PZT}} \sum_{k=1}^{N} \left( k + \frac{\beta - 1}{2} \right) \right] \times E_{\text{struc}} \sum_{k=1}^{N} \left( \frac{\beta^3}{12} + \beta \left( k - 1 + \frac{\beta}{2} \right)^2 \right)
\]

\[
\times \left[ \left( \frac{1}{12} - \beta \right)^3 + 1 - \beta \left( k + \frac{\beta - 1}{2} \right)^2 \right] \right]^{-1}
\]

Letting

\[
F_{n0} = -\frac{M_c A_n V_0}{m(\lambda_n^2 - w^2)} \left[ \phi_n'(x_a) + \phi_n'(x_b) \right].
\]

Then equation (9) can be expressed as

\[
F_n(t) = F_{n0} e^{i\omega t}.
\]

Thus, substituting equations (7) and (11) into equation (6), the general solution of the dynamic equation for the multimorph bending PZT actuator becomes

\[
w(x, t) = \sum_{n=1}^{\infty} \phi_n(x) F_{n0} e^{i\omega t}.
\]
3. Comparison with theory, ANSYS analysis and experiment

3.1. Experimental apparatus set-up and procedures

When a PZT actuator is designed, the design parameters to be checked are the maximum displacement, the generative force and the mode frequency. In order to verify the validity of the analytical results on these parameters derived in section 2, the results are compared with ANSYS simulation and experimental results. Figure 3 shows the schematic of the experimental set-up. The displacement is measured using an MTI-2000 Fotonic sensor with a sensitivity of 0.02 μm mV⁻¹. The MTI-2000 Fotonic sensor is a dual-channel, fiber-optic measurement system that performs non-contact displacement and vibration measurements. In the measurement, sinusoidal waveform electric fields were applied to the actuator. A voltage was applied in a bipolar waveform at 0.05 Hz. The measured data were collected and analyzed by using DSP Siglab and Matlab. In the experiments, a commercial multimorph, manufactured by Morgan Electro Ceramics, was used. The properties of the PZT material are shown in table 1.

The size of the PZT actuator is 16 mm x 6 mm x 0.48 mm. The material is composed of PbO (66%), ZrO₂ (21%) and TiO₂ (11%). The total number of layers is 20 and each layer thickness is 20 μm. The electrode consists of Ag–Pd. The thickness of each covering layer that is attached to both sides of a multimorph is 40 μm. Titanium is used as the material of the covering layer.

3.2. Experimental results and discussion

The transverse displacement of a multimorph as a function of the voltage applied across the thickness of the PZT is shown in figure 4(a). The displacement generally increases with increasing applied electric field, showing hysteretic motion. The hysteretic curve in figure 4(a) is acquired when a periodic input with voltage between −10 and 10 V is applied to the PZT. The displacement obtained when the applied voltage is decreased from 0 to −10 V is somewhat larger than when the voltage is increased from −10 to 0 V. The maximum displacement at the tip of the actuator is measured as ±36.96 μm in the experiment. The maximum displacement of the actuator means the maximum amplitude of the hysteretic curves responding to the harmonic input. Figure 4(b) shows the frequency response function of the multimorph when the actuator is excited by a banded-white noise from 10 Hz to 20 kHz. The fundamental natural frequency of the PZT actuator is 750 Hz, as shown in figure 4(b). The PZT actuator is also analyzed by ANSYS, a commercial FEM program. The following three properties—the compliance, PZT coupling and the relative permittivity—are used in this simulation. Figures 5(a) and (b) show simulation results of the dynamic
Table 2. Comparisons of experimental and analytical results of a multimorph PZT.

<table>
<thead>
<tr>
<th></th>
<th>Theory</th>
<th>Experiment</th>
<th>Analysis with ANSYS</th>
<th>Experiment (provided by manufacturer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement (μm)</td>
<td>±38.20</td>
<td>±36.96</td>
<td>±42.95</td>
<td>±38.54</td>
</tr>
<tr>
<td>Force at the tip (N)</td>
<td>0.2475</td>
<td>—</td>
<td>0.2422</td>
<td>0.2178</td>
</tr>
<tr>
<td>1st mode (Hz)</td>
<td>795.2</td>
<td>750</td>
<td>749.1</td>
<td>750</td>
</tr>
<tr>
<td>2nd mode (Hz)</td>
<td>4983.4</td>
<td>4837.5</td>
<td>4892.1</td>
<td>—</td>
</tr>
<tr>
<td>3rd mode (Hz)</td>
<td>13954</td>
<td>14544</td>
<td>14102</td>
<td>—</td>
</tr>
</tbody>
</table>

Figure 5. (a) Plots of first four mode shapes of PZT actuator and (b) PZT actuator motion at the end tip at 5 Hz harmonic excitation.

The theoretical results by the Bernoulli–Euler model and experimental results are summarized in Table 2. Even though the theoretical results show a good agreement with the experimental data, there is an allowable discrepancy in the two results. This is due to a lot of factors such as the changing boundary condition in the experiment, inaccurate material properties, modeling-induced error and simulation truncation error. In general, the natural frequencies by FEM are higher than those measured in the experiment, because the experiment does not ensure the clamping conditions. As shown in Table 2 where theoretical, experimental and FEM results are compared, the frequencies of the three modes are not consistent and the experimental values are not always lower than those of the theoretical and FEM results.

The correlation between theoretical and experimental results ensures that the theoretical predictions can be used as a design guideline for the multilayered bimorph PZT actuator at a specific layer number, such as the natural frequency, maximum displacement and resultant force at the tip. The multilayer-type actuator gives better performance in every aspect, compared with the single-layer (PZT–electrode–PZT) type.

4. Design of a flexure hinge displacement amplifier

Controlling the design parameters such as the stacked layer number, size and material properties, the resultant outputs such as the tip displacement, resultant force and natural frequencies of the PZT actuator might meet the system requirements. However, the resultant displacement induced by the PZT multimorph under the low driving voltage and the limited size requirement is not enough for the required stroke for the focusing and tracking directions. Therefore, in order to extend the allowable stroke in both tracking and focusing motions of an optical pick-up, we consider a novel flexure hinge mechanism connected to the PZT actuator. The proposed structure also exhibits decoupled motions in the focusing and tracking directions.

4.1. Basic design of the flexure hinge mechanism

An ideal flexure hinge permits the relative rotation of the rigid adjoining members, while prohibiting any other types of motion. A typical flexure hinge consists of one or two cutouts that are machined in a blank material. The flexure hinges are modeled and analyzed as Euler–Bernoulli beams, which are subjected to bending produced by forces and moments. The rotation angles are formulated by using Castigliano’s second theorem [18]. Figure 6 illustrates the right circular flexure hinge employed for amplifying the stroke displacement. It is confirmed from Figures 7 and 8 how the flexure hinge mechanism is connected to the PZT actuator. In this work, the amplified stroke displacement is demanded in the vertical direction (z axis). Thus, $M_y$ induced by the PZT actuator
rotates the flexure hinge of figure 6 about the y axis ($\theta_y$). As a consequence, the opposite position to the position connected with the flexure hinge is amplified (see figure 8). The rotation–moment relationship is of the form

$$
\begin{bmatrix}
\theta_z \\
\theta_y
\end{bmatrix}
= 
\begin{bmatrix}
c_{11} & 0 \\
0 & c_{22}
\end{bmatrix}
\begin{bmatrix}
M_z \\
M_y
\end{bmatrix},
$$

where $\theta_z = \frac{\partial U_e}{\partial M_z}$, $\theta_y = \frac{\partial U_e}{\partial M_y}$, $c_{11} = \frac{12}{Eb} I_1$, $c_{22} = \frac{1}{Gb} J_1$, (13)

In the case of right circular flexure hinges, the following conditions are satisfied:

$$
t(x) = 2R + t - [x(2R - x)]^\frac{1}{2}, \quad c = a = R, \quad \beta = \frac{t}{2c}.
$$

(15)

Here the design variables ($R$, $c$, $a$, $t$) are shown in figure 6. Equation (13) is combined with equations (15) to formulate the compliance equations for the circular flexure hinge, namely

$$
c_{11} = \frac{12}{Eb t^2 (2 + \beta)^2} \times \left[ \frac{3 + 4\beta + 2\beta^2}{2(1 + \beta)} + \frac{3(1 + \beta)}{\sqrt{\beta(2 + \beta)}} \tan^{-1} \sqrt{\frac{2 + \beta}{\beta}} \right]
$$

(16)

$$
c_{22} = \frac{1}{Gb t^2 (2 + \beta)^2} \times \left[ \frac{3 + 4\beta + 2\beta^2}{2(1 + \beta)} + \frac{3(1 + \beta)}{\sqrt{\beta(2 + \beta)}} \tan^{-1} \sqrt{\frac{2 + \beta}{\beta}} \right].
$$

(17)

Finally, equations (13) and (17) give

$$
\theta_y = \frac{M_y}{M_0} \times \left[ \frac{3 + 4\beta + 2\beta^2}{2(1 + \beta)} + \frac{3(1 + \beta)}{\sqrt{\beta(2 + \beta)}} \tan^{-1} \sqrt{\frac{2 + \beta}{\beta}} \right],
$$

(18)

where $M_y$ can be replaced with $M_0$, which is the resultant moment occurring at the tip of the PZT actuator.
4.2. Experiments of stroke amplifier model

In this paper, a hinge model is designed to use a torsion elastic deformation, as shown in figure 7. The displacement amplifier mechanism is determined by the ratio between the PZT displacement, $L_2$, and the amplified stroke, $L_1$. Here, a right circular hinge structure is adapted, because it shows a better performance than other types of hinges from the standpoint of precision. The stress analysis of the proposed hinge model is performed using the ANSYS FEM software, and the simulation result is shown in figure 9. In the static analysis, the design variables (length, width and thickness) of the proposed flexure hinge model are set at 1, 1 and 0.2 mm, respectively. We choose Be–Cu as the material of the flexure hinge to meet the allowable stress.

The ratio of the displacement amplifier is analytically predicted to be 4.92. Figure 10 shows the experimental setup to measure the flexure hinge mechanism of the stroke amplifier. As shown in figure 11, the experimental stroke ratio is measured as about 4.5. It is also observed in figure 12 that frequencies of vibration modes are slightly diminished.

To decrease the discrepancy between the analytical and experimental results on the stroke ratio, the following two design factors can be considered. The first factor is that the flexural rigidity of a connected beam should be very high. The second one to be considered is that the output force at the edge of the PZT actuator should be large enough to deform the flexure hinge elastically in torsional motion.

5. Design of and experiments with an optical pick-up actuator

Because the PZT material has a large output force and fast response, it can be applied to an optical pick-up actuator if it is combined with a flexure hinge to extend its maximum stroke. Based on the theoretical analysis and experimental verification carried out in the paper, we propose a slim-type PZT actuator with a total size of 16 mm $\times$ 14.6 mm $\times$ 3 mm. Figure 13 shows a schematic of the proposed actuator using four parallel PZT bimorphs and a displacement amplifier with a novel flexure hinge structure. The novel structure enables the decoupled...
movements between the focusing and tracking directions. When the horizontal bimorphs are driven in the focusing directions, the optical pick-up unit shows the amplified focusing motion. Also the tracking motion is driven by the two vertical bimorphs moving in the tracking direction without amplification by the stroke amplifier, as shown in figure 13(a).

Figure 14 shows the manufactured prototype of the proposed actuator model, where the moving range is ±400 μm at ±15 V and the first natural frequency is 750 Hz. As shown in figures 15 and 16, the experimental results on the focusing stroke, hysteresis curves and the first natural frequency of the PZT actuator are similar to those of the half-actuator model in figure 7. Figure 15 shows the comparisons of three hysteretic curves before and after amplification. One is the focusing displacement at the tip of the PZT multimorph before amplification. The other (blue line) represents the amplified displacement of the half-model with the stroke amplifier. The red line plot is the displacement of the final PZT actuator model measured at the lens center by the flexure hinge structure. Figure 16 shows the frequency response plot, showing that the first resonant frequency in the transverse direction of the assembled pick-up actuator is 750 Hz.

Also, by the symmetric structure of the flexure hinge amplifier, the radial tilt at the lens center is expected to be reduced. The tilting problem is the critical issue in slim and small-form-factor precision devices, especially SFF optical
disk drives, since tilt angle leads to coma aberration. Thus, to confirm the effect of the focusing motion on the tilt angle of the flexure hinge amplifiers, we measure the tilt motion of the proposed model through the related experiment. It is observed in figure 17 that the radial tilting motion is within the range between 0.001° and 0.0017°. Also, the frequency of dynamic motion in the focusing direction increases. These experimental results are relatively higher or robust values in comparison with those of the conventional optical pick-up with four-wire-type suspension. Hence, the proposed actuator meets the general specifications of the maximum stroke, the resultant force and the dynamic characteristics for the optical pick-up actuators. It is concluded that the proposed actuator model is applicable to various precision devices of slim or small-form-factor types for actively controlling a movable device.

6. Conclusion

In this paper, we propose a miniaturized optical pick-up actuator using a multilayered bimorph PZT for the application of slim or small-form-factor optical disk drives. Based on our preliminary work on the theoretical analysis for the multilayered piezoelectric structure [15], we predict the output characteristics of the proposed model of a cantilever stacked beam including the multilayered bimorph PZT actuator. We also investigate whether the natural frequency, the resultant force and the maximum displacement of the actuator model satisfy the requirements for the slim and small-form-factor optical devices. A novel flexure hinge mechanism is used as the displacement amplifier to extend the allowable stroke in both tracking and focusing motions. The prototype of the proposed model was manufactured using commercial bimorph PZTs. The proposed pick-up actuator can make both tracking and focusing motions simultaneously without unnecessary effects caused by a tilting motion. Experimental results agree well with the analytical and numerical predictions. The stroke amplification ratio is measured at about 4.5 in experiments. Based on the theoretical analysis and the preliminary experiments, we propose a prototype model for a new PZT actuator with an allowable small size, enlarged moving range and fast frequency response, which can be applicable to slim or small-form-factor optical disk drives.

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References