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초소형 광디스크 드라이브용 PMN-PT 액츄에이터 설계

A PMN-PT Pickup Actuator for Small Form Factor Optical Disk Drives

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Key Words : PMN-PT Bimorph, Ferroelectric(강유전체), Piezoelectric material(압전소자), Actuator(구동기), Optical Pickup (광픽업), Displacement amplifier(변위 확대), Electrostrictor

ABSTRACT

본 연구에서는 PMN-PT bimorph actuator 를 이용하여 초소형 광디스크 드라이브용 광픽업 구동기를 제작하였다. 최근에 휴대용 기기에서의 고용량 정보 저장기기에 대한 필요성이 대두됨에 따라 착탈식이 가능한 수 기가급 초소형 광디스크 드라이브가 개발중에 있다. PMN-PT 는 약 1.5kV/cm 이하의 전기장에서는 PZT 같은 압전 소자와 마찬가지로 입력 전압에 대한 변형률이 선형성을 나타내는데, 사용된 PMN-PT 는 PZT 의 약 3 배 가까운 압전 상수값을 나타내었다. 보 끝단에 외부 힘이 작용할 때 PMN-PT bimorph 구동기가 낼 수 있는 수직 방향의 힘과 변위에 대해서 일반적인 적층 형태로 이론적인 해석을 수행 하였다. 그리고 이 bimorph 로 구동될 Cymbal 형태의 변위 확대 기구의 변위에 대한 이론적인 모델을 제시하고, 이를 이용하여 2 개의 bimorph 로 2 축을 동시에 구동하는 픽업 구동기를 제작하였다. 3 개의 제작된 prototype 으로 실험을 수행하여 예상 변위량과 잘 일치함을 보였다. 또한, 상용 해석 프로그램인 Matlab 과 Ansys 를 이용하여 Cymbal 확대 기구의 여러 파라미터에 따른 구동 성능의 민감도를 확인해 보았다.

1. Introduction

Since CD(Compact Disk) drives were developed by Philips, ODD(Optical Disk Drive)s have been leading data storage devices. Recently BD(Blue-ray Disk) drives are being launched by major ODD companies as a next generation's high density optical data storage which can store several hours' HDTV movies.

Nowadays needs for mobile data storage devices have been largely increased since mobile devices like mobile phones and PDA's became widely used. Although the standard form factor of the mobile ODD is not determined yet, its form factor will be expected to be similar to an IBM's microdrive. And the height of the pickup actuator is a one of the most critical issues for compact mobile ODDs [1].

PMN-PT materials are used for driving parts of a pickup actuator. Electrostrictive actuators such as PMN-PT are solid state actuators like PZTs. PMN-PT actuators have larger piezoelectric constants and elastic modulus than PZT's. Also they exhibit less hysteresis on the order of 3% than PZT's. Because of their direct electric-mechanical effects, additional parts like magnets or yokes in conventional electro-magnetic pickup actuators are not necessary.

In this paper, we propose a new type's pickup actuator using PMN-PT bimorph actuators. A transverse motion in focusing direction is caused by the cymbal type displacement amplifier, so simultaneous motions of two directions are able to be achieved by two bimorph actuators. Theoretical models of the bimorph actuator and cymbal type amplifier are proposed respectively and verified by experiments. Experimental results using prototypes agree well with the analytical predictions. And we propose a slim type pickup actuator model with 1.5 mm's height using the analytical models for a small form factor optical disk drives.

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2. Modeling of the multi-layer PMN-PT bimorph actuator

2.1 Comparison of PMN-PT and PZT

In recent years, relaxor-based ferroelectric single crystals like PMN-PT have attracted considerable attention due to their extremely high piezoelectric properties. They have ultrafast piezoelectric response and large electric field strain values with low hysteresis which are markedly superior to those of conventional PZT ceramics [2].

Generally it is known that PMN-PT actuator cannot be used in a bipolar mode like a piezoelectric actuator because of its quadratic relationship between voltage and displacement [3]. Commonly, the S(E) relations in PMN-PT crystals can be well described as follows.

$$S_1 = d_{31}E_3 + M_{31}E_3^{\ 2} \qquad (1)$$

Where $d_{31}E_3$ is the piezoelectric effect and $M_{31}E_3^{\ 2}$ is the electrostrictive effect. However, as shown in Fig. 1, main contribution for strain is the piezoelectric effect in the low electric field because the magnitude of the electrostrictive constant M_{31} is extremely small.

When the applied electric field is smaller than approximately 1.5 kV/cm, we can figure almost all of the strain induced by a piezoelectric effect [4]. And in that condition, we can suppose that PMN-PT actuators have linear electric field-strain relations like PZT. There 1.5 kV/cm is a sufficiently large input value for personal mobile devices which usually use electric voltages lower than several volts.

2.2 Static analysis of the PMN-PT actuator under a external tip force

In a bimorph actuator, PMN-PT layer is bonded to the top and bottom surfaces of the center metal electrode and it is driven by voltages of the opposite polarity for a parallel type. General n-layer bimorph actuator is configured in Fig. 1. When electric field is biased on the each electrode, PMN-PT layers above x-axis go through extensions and the other side's layers go through contractions. The location at x=0 is fixed and right end of the beam is free. By the strains of each PMN-PT layer, multilayer bimorph actuator bends its transverse direction.

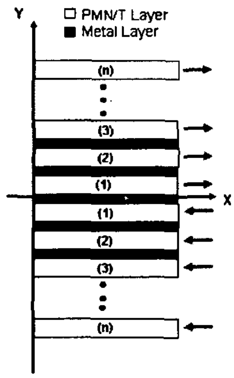

Fig. 1 Schematic configuration of the multilayer PMN-PT bimorph actuator

The linearized constituent equations of a upper and lower PMN-PT layers under a low electric field is as follows,

Upper i-th PMN-PT layer :

$$S_{1i}{}^{P} = s_{11}{}^{E} T_{1i}{}^{P} - d_{31} E_3 \qquad (2)$$
$$-D_{3i}{}^{P} = d_{31} T_{1i}{}^{P} - \varepsilon_{33}{}^{T} E_3$$

Lower i-th PMN-PT layer:

$$S_{1i}{}^{P} = s_{11}{}^{E} T_{1j}{}^{P} + d_{31} E_3 \qquad (3)$$
$$D_{3i}{}^{P} = d_{31} T_{1i}{}^{P} + \varepsilon_{33}{}^{T} E$$

where $s_{11}{}^{E}$, d_{31} and ε_T are the elastic compliance, piezoelectric constant, and relative dielectric constant respectively. And constituent equation of the electrode metal layer is also described as follows,

$$S_{1i}{}^{m} = s_{11}{}^{m} T_{1i}{}^{m} \qquad (4)$$

Internal energy density of the PMN-PT layer is expressed such as,

$$u_i{}^{P} = \frac{1}{2} S_{1i}{}^{P} T_{1i}{}^{P} + \frac{1}{2} D_{3i}{}^{P} E_3 \qquad (5)$$

Substituting of Eqs. (2),(3) and (4) into Eq. (5) gives

Upper i-th layer:

$$u_i{}^{pup} = \frac{1}{2} s_{11}{}^{E} T_{1i}{}^{2} - d_{31} E_3 T_{1i}{}^{P} + \frac{1}{2} \varepsilon_{33}{}^{T} E_3^{2} \qquad (6)$$

Lower i-th layer:

$$u_i{}^{plow} = \frac{1}{2} s_{11}{}^{E} T_{1i}{}^{2} + d_{31} E_3 T_{1i}{}^{P} + \frac{1}{2} \varepsilon_{33}{}^{T} E_3^{2} \qquad (7)$$

$$u_i{}^{mup} = \frac{1}{2} s_{11}{}^{m} T_{1i}{}^{m2} = u_i{}^{mlow} \qquad (8)$$

A total internal energy is a summation of volume integration of each layers' energy densities. Due to the axis of symmetry, the total internal energy is as follows,

$$U = U^P + U^m = 2\sum_{i=1}^{n} U_i{}^{pup} + 2\sum_{i=1}^{n} U_i{}^{mup} \qquad (9)$$

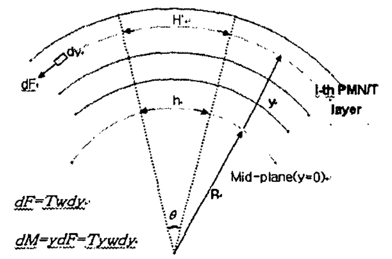

Fig. 2 Bending deformation of the multilayer bimorph actuator

Using the curvature k, we can get the total internal energy of the multilayer bimorph actuator by the volume integration.

$$U = \frac{1}{2} A\left(\frac{F^2 h^3}{3A^2} - \frac{F}{A^2}\frac{d_{31} h^2 J_P'}{s_{11}{}^{E}} E_3 + \frac{d_{31}{}^{2} J_P'^{2} h}{A^2 s_{11}{}^{E2}} E_3{}^{2}\right) \qquad (10)$$
$$+ \frac{1}{2} nwh\left(\varepsilon_{33}{}^{T} - \frac{1}{s_{11}{}^{E}} d_{31}{}^{2}\right) E_3{}^{2} t_P$$

$$\text{where } A = \frac{I_P'}{s_{11}{}^{E}} + \frac{I_m'}{s_{11}{}^{m}}, \quad J_P' = 2w\sum_{i=1}^{n}\int_{\frac{2i-1}{2}t_m+(i-1)t_P}^{\frac{2i-1}{2}t_m+it_P} y\,dy$$

$$I_P' = 2w\sum_{i=1}^{n}\int_{\frac{2i-1}{2}t_m+(i-1)t_P}^{\frac{2i-1}{2}t_m+it_P} y^2\,dy$$

$$I_m' = \frac{1}{12} w t_m{}^{3} + 2w\sum_{i=2}^{n}\int_{\frac{2i-3}{2}t_m+(i-1)t_P}^{\frac{2i-1}{2}t_m+(i-1)t_P} y^2\,dy$$

In the case of parallel type bimorph actuator, the relation between electric field and voltage can be expressed as

$$V = t_P E_3 \qquad (11)$$

When external force is applied at its tip, tip deflection of the actuator is a partial derivative of the total energy.

$$\Delta = \frac{\partial U}{\partial F} = \frac{h'^3}{3A}F - \frac{d_{31}J_P'h'^2}{2As_{11}^E t_p}V \qquad (12)$$

From Eq. (12), we can get a tip resultant force at each quasi-equilibrium states.

$$F = \frac{3A}{h^3}(\Delta - \Delta_0) \qquad (13)$$

where $\Delta_0 = -\frac{h^2 d_{31}J_P'}{2As_{11}^E t_P}V$: *free tip displacement*

3. Design of the cymbal type displacement amplifier

Many kinds of flextensional displacement amplifiers have been studied in ultrasonic actuator applications. It is known that cymbal type actuators have a large displacement with zero center angle after deformation and a small cyclic hysteresis relative to other types' flextensional amplifiers [6].

Here the two types of models are introduced. One of the model is for a flextension dominated deformation model when the tilting angle of the cymbal end cap is small. And the other is for a rotation dominated model in case the tilting angle is larger than that of flextension dominated region. To determine dominant motion according to initial tilting angles, we use minimum transverse displacements of the two models. In the analysis, the cymbal end cap thickness and initial tilting angle is very important factor to design a displacement amplifier.

3.1 Analysis of the cymbal type amplifer in the flextension dominated motion

In this flextension dominated model, the force resulted from the tip of PMN-PT bimorph actuator is the main factor for a transverse displacement. It is because the cymbal amplifier is very difficult to be deformed in the case of small initial tilting angles θ_0.

Fig. 3 is a schematic configuration of a flextension dominated model. The PMN-PT tip force F resulting transverse deflection δ and the center angle ϕ is given by

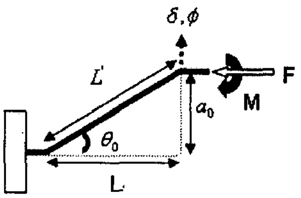

Fig. 3 Configuration of a flextension dominated model

$$\delta_1 = \frac{FL'^3}{3EI}\sin\theta_0\cos\theta_0 \qquad (14)$$

$$\phi_1 = \frac{FL'^2}{2EI}\sin\theta_0 \qquad (15)$$

And the center angle by external moment M is given by

$$\phi_2 = -\frac{ML'}{EI} \qquad (16)$$

To keep the center angle horizontal stay zero, angle ϕ_1 and ϕ_2 should be equal. This yields

$$M = \frac{FL'}{2}\sin\theta_0 \qquad (17)$$

Therefore the deflection by external moment is expressed as follows,

$$\delta_2 = -\frac{ML'^2}{2EI}\cos\theta_0 = -\frac{FL'^3}{4EI}\sin\theta_0\cos\theta_0 \qquad (18)$$

As a result, the whole resultant transverse displacement of the flextension dominated model is represented as

$$\delta_{flex} = \delta_1 + \delta_2 = \frac{FL^3}{3EI}\frac{\sin\theta_0}{\cos^2\theta_0} - \frac{FL^3}{4EI}\frac{\sin\theta_0}{\cos^2\theta_0} \qquad (19)$$

3.2 Analysis of the cymbal type amplifer in the rotation dominated motion

This model is the case the whole motion is dominated by rotation of the curved edges when the initial tilting angle θ_0 is large enough to deform the amplifier by the small tip forces.

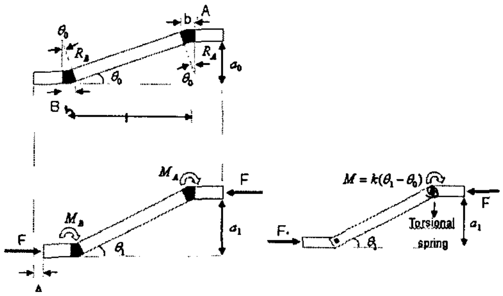

Fig. 4 Configuration of a rotation dominated model

As shown in Fig. 4, point A and B are the centers of rotation of the cymbal amplifier. A rotation dominated model consists of a torsional spring at point A and a hinge at point B. And the beam is supposed as a rigid body.

From the geometric condition,

$$(L-\Delta)^2 + a_1^2 = L^2 + a_0^2 \qquad (20)$$

Where a_0 is a initial height and a a_1 is a height after deformation of the cymbal amplifier. For a small actual tip displacement of the PMN-PT bimorph actuator Δ, a transverse displacement yields

$$\delta = a_1 - a_0 = \sqrt{a_0^2 + 2L\Delta} - a_0 \qquad (21)$$

In case the transverse displacement initial height of the amplifier is small, Eq. (21) is expressed as

$$\delta \cong \frac{L}{a_0}\Delta \qquad (22)$$

In the meantime, from the moment balance equation,

$$\delta = \frac{c_0(\Delta_0 - \Delta)}{\frac{2EI}{bL} - c_0(\Delta_0 - \Delta)} \qquad (23)$$

Using Eqs. (22) and (23), we can get a second order equation about actual displacement Δ .

$$c_0 L\Delta^2 + (\frac{2EI}{b} - c_0 L\Delta_0 + c_0 a_0)\Delta - c_0 a_0 \Delta = 0 \qquad (24)$$

Solving this equation yields

$$\Delta = \frac{-2EI + (a_0 + L\Delta_0)c_0 b + \xi^{0.5}}{2c_0 Lb} \qquad (25)$$

$$\xi = 4E^2I^2 + 4(a_0 - L\Delta_0)EIc_0 b + (L\Delta_0{}^2 + 2a_0\Delta_0)c_0{}^2 Lb^2 + c_0{}^2 a_0{}^2 + b^2$$

Therefore transverse displacement of the cymbal amplifier is

$$\delta_{rot} = \frac{L}{a_0}\Delta \qquad (26)$$

And to determine the point at which the motion changes flextension dominated region to rotation dominated region, we take minimum values between δ_{flex} and δ_{rot}.

4. Analytical and experimental results of PMN-PT bimorph actuators and displacement amplifiers

4.1 Comparison of the analytical results and experimental results of a PMN-PT bimorph actuator

In order to confirm the previous formulations, we performed Ansys simulations and experiments. Fig. 5 and Table. 1 show a experimental setup and material properties of the PMN-PT bimorph actuator respectively.

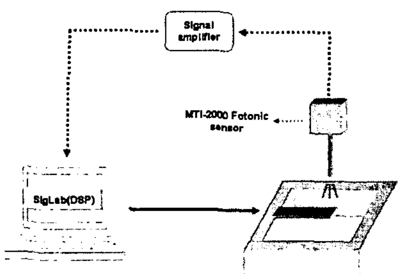

Fig. 5 Experimental setup for a PMN-PT bimorph actuator and pickup actuator

Property	Values	Units
Density	7843	Kg/m3
Dielectric const.	4991	
Coupling factor	0.922	
d31	-652E-12	m/V
Young's modulus	144	GPa

Table. 1 Material properties of the PMN-PT

As shown in Table. 1, a PMN-PT single crystal has superior properties to the PZT. Especially piezoelectric constant d_{31} and Young's modulus are almost three times than PZT's.

The whole size of the used 1-layer PMN-PT bimorph actuator is 16 x 6 x 0.45 mm. A 50 um thick stainless steel is bonded as a electrode layer between two 200 um thick PMN-PT layers. The following analyses and experiments were performed under a AC biased voltage between -10~10V.

By the numerical calculation, the displacement and blocking force of the tip were expected to be 27.4 um and 132 mN respectively. And 29.9 um of tip displacement was expected by Ansys simulation. In the experiment, the tip displacement at 5Hz is 26 um and hysteresis is 2.4%. This hysteresis value is 10% smaller than that of PZT.

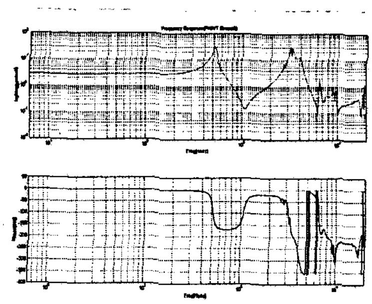

Fig. 6 FRF of the PMN-PT actuator

Fig. 6 shows a measured frequency response of the PMN-PT actuator. The first resonance of the actuator is 510Hz. Experimental first resonance is lower than the theoretical value of 829 Hz by Euler-Bernoulli beam theory. It is because the boundary condition of the actuator is not fully clamped.

A multilayer PMN-PT bimorph actuator shows better dynamic performance than a 1-layer bimorph actuator in the same size in every aspect like displacement, resultant force and natural frequencies.

4.2 Experiments of the pickup actuators using cymbal type displacement amplifier

Fig. 7 shows a prototype model driven by two PMN-PT bimorph actuators. Same direction's motion of the two actuators gives tracking motion and different direction's motion gives transverse motion by the cymbal amplifiers in a focusing direction.

The entire dimension of the pickup actuator is 16 x 6 x 12 mm including PMN-PT bimorph actuators. The thickness of the cymbal is 50 um and width is 2 mm. There is a bobbin part for a lens between two cymbal amplifiers, and flexure hinges are used as a motion guide to decrease a tangential tilt. By the symmetric structure, very small radial tilt at the lens center is expected. To confirm the analytical results according to the initial tilting angle of the cymbal amplifiers, we made three prototypes having different initial tilting angles.

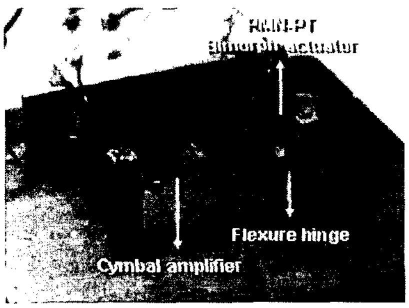

Fig. 7 Prototype of the pickup actuator using cymbal displacement amplifiers

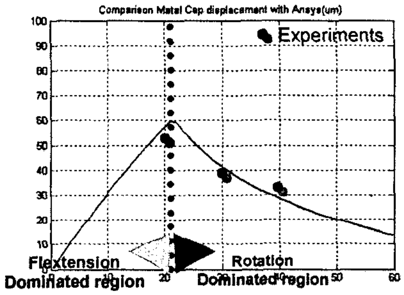

Fig. 8 Comparison of the analytical results and experimental results

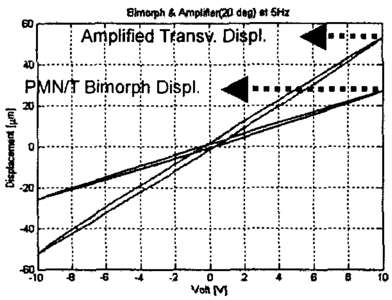

Fig. 9 Comparison of the hysteresis curve between displacement of the PMN-PT bimorph and its amplified transverse displacement(θ_0 = 20 deg.)

Fig. 8 shows experimental results of the three prototypes under a 5Hz's AC input between -10~10V. In this figure, we can see expected static displacements of the cymbal amplifiers agree well with measured maximum displacements. Measured results are 52, 38, 33 um in the case of 20, 30, 40 degrees of the initial tilting angles respectively. Maximum transverse displacement is expected around 20 degrees of a initial angle. In other words, cymbal amplifier can be divided by two regions which is flextension dominated region and rotation dominated region and it has a maximum displacement around its transition point.

Fig. 9 shows the comparison of two hysteresis curves. One is for the PMN-PT bimorph actuator and the other is for the pickup actuator having 40 deg. initial tilting angle The magnitude of hysteresis for pickup actuator is about 3.25% which is also very small value. In this case, the amplification factor is approximately 2.

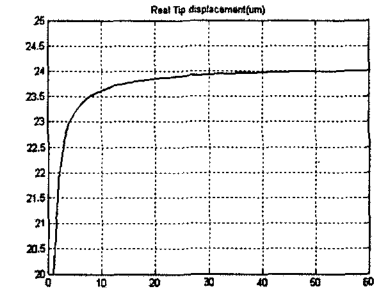

Fig. 10 Analytical actual tip displacement of the PMN-PT bimorph actuator according to the cymbal amplifiers' initial tilting angles

Previously, the bimorph tip displacement under free load condition was analytically expected to be 27.4 um. Fig. 10 shows analytical tip displacements in focusing motion. In focusing motion of the pickup actuator, two bimorph actuators go through external load by cymbal amplifiers. At 20 deg., a analytical result is 23.8 um and experimental result is 21 um. In the Fig. 12, the tip displacements converges to about 24 um over 20 deg.. It means that motion of the amplifier goes into the rotation dominated region.

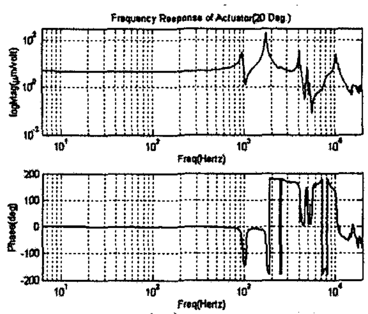

Fig. 11 FRF of the pickup actuator(θ_0 = 20 deg.)

As shown in Fig. 11, first resonant frequency of the pickup actuator in focusing direction is 956Hz. The 20 and 30 deg. cases also have similar first resonant frequencies. These are relatively higher values than those of the conventional 4-wire type pickup actuators.

4.3 Parametric sensitivity of the cymbal amplifier

Fig. 12 shows a change of maximum displacements as length L increases from 3 mm to 3.5 mm with a fixed thickness of 0.05 mm. And Fig. 13 is a change of maximum displacements as thickness t decreases from 0.03 mm to 0.07 mm with a fixed length of 3 mm. From two figures, we can guess that thickness of the cymbal amplifier is very sensitive parameter for a static design.

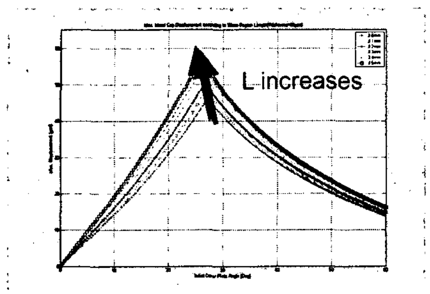

Fig. 12 Static sensitivity upon a cymbal length L

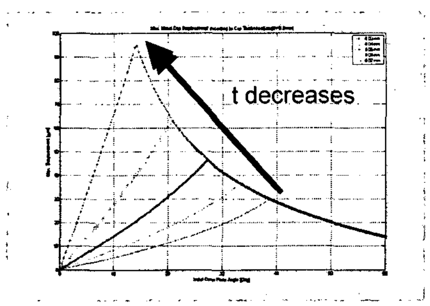

Fig. 13 Static sensitivity upon a cymbal thickness t

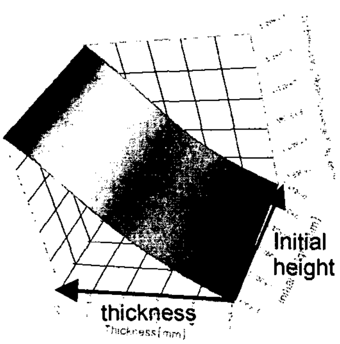

Fig. 14 1st resonant frequencies with varying design parameters

Fig. 14 is a one of the parametric dynamic studies depending on thickness t and its initial height a_0. The first vibration mode is a focusing motion caused by cantilever mode by bimorph actuators and varies from 989Hz to 1196 Hz with 10% varying parameters from the prototype. The study tells that first and second resonance is largely affected by thickness of the cymbal amplifier.

5. Conslusions

In this paper, we proposed a new pickup actuator using PMN-PT bimorph actuators for a application of small form factor ODDs. The PMN-PT has a better electro-mechanical properties than PZT. The theoretical equation for a PMN-PT multilayer bimorph actuator was derived using the internal energies and we performed static analyses about resultant tip displacements and forces. For a displacement amplification, cymbal type amplifier was proposed. Because this amplifier makes a vertically amplified stroke about horizontal displacement by PMN-PT bimorph actuators, the proposed pickup actuator can make tracking and amplified focusing motions simultaneously. The prototypes using PMN-PT bimorph actuators were manufactured, their experimental results agreed well with numerical predictions. The prototype using cymbal amplifiers with 40 degrees' initial tilting angle has a tracking displacement of 26 μm and a focusing displacement of 52 μm.

Acknowledgement

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