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Electro-thermally activated rotary micro-positioner for slider-level dual-stage positioning in hard disk drives

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Abstract: Slider-level micro-positioners are useful to assist a voice coil motor to perform fine heat positioning over Tb/in² magnetic disk. Recently, a new kind of slider-level micro-positioners were developed using thermal unimorph of Si/SU8 composite. It has advantages of very small foot print and high mechanical resonant frequency but its stroke generation is inadequate, with 50nm dynamic stroke at 1kHz. There is a need for a larger thermally induced stroke. This paper presents a rotary design of electrothermal micro-positioner to address the stroke requirements without consuming more power or decreasing the mechanical resonant frequency. Experimental studies show the present rotary design can produce 6 folds larger displacement, as compared to the previous lateral design, while possessing a 35 kHz resonant frequency of. In addition, simple analytical models were developed to estimate: i) the rotational stiffness and system's natural frequency, ii) thermal unimorph bending and stage rotation, and iii) system's thermal time constant for this rotary electro-thermal micro positioner. This study found that this rotary electro-thermal micro-positioner can meet the basic stroke requirement and high mechanical resonant frequency for moving slider, but its thermal cut-off frequency needs to be increased further.

1. Introduction

As the recording areal density of magnetic media for hard disk drive (HDD) increases towards a 4 Tb/in², it becomes more challenging for the existing single-stage positioner, i.e. a voice coil motor (VCM) to perform accurate head positioning. At this areal density (corresponding to 1 million tracks per inch (TPI)), the data track is as fine as 25nm wide and the allowable track misregistration is 2.5nm (3 σ value) [1]. Dual-stage positioning scheme (see Figure 1a) can assist the coarse primary driver to achieve finer head-positioning at higher speed [1-15]. There are three locations for deploying the dual-stage actuators, namely suspension-level, slider-level and head-level. Suspension-level milli-actuators have been adopted in commercial HDDs with sub 1 Tb/in² data density.

As the data density goes beyond 1 Tb/in², next-generation dual-stage positioning system needs to move a femto slider faster at a lesser stroke (< 0.2 μ m). The servo-bandwidth of current dual-stage scheme using suspension-level milli-actuator is no better than 3kHz due to interference by suspension dynamic (with 5-12 kHz resonance) [2-3]. In contrary, better servo bandwidth is possible using the slider-level micro-positioner, which is collocated with the read-write head and has a lower inertia. Various micro-actuators have been developed so far for the slider-level micro-positioner: electrostatic comb drives [4], or electrostatic parallel plates [5-6], piezoelectric unimorphs [7-8], piezoelectric

extender [9-11] or electro-thermal micro-actuators [12-15]. They can move a slider linearly using a translation stage [4, 7] or swing the slider using a rotary (angular) stage [5-8]. A rotary stage offers the advantages of stroke magnification and reduced rotation inertial if its flexures are properly designed.

Bi-directional travel of these micro-positioners is generated by bipolar activation of two opposing micro-actuators. For example, in electrostatically driven micro-positioners [4-6], a pair of comb drives was alternatively activated to attract a moving stage towards a direction or the reverse. A piezoelectric extender itself can produce the stroke reversal upon reversing the voltage polarity [9-11]. But, most piezoelectrically driven micro-positioners are driven in the push-pull mode by a pair of piezoelectric micro-actuators, either piezoelectric unimorphs [7-8] or extenders [9-11]. A thermal micro-actuator, such as a V-shape expansion flexure [12] or a thermal unimorph [13-15], produces only one directional stroke upon heating. A mirrored pair of thermal micro-actuators can produce bidirectional stroke upon alternate heating, with the active micro-actuator deforming the in-active one [12-15].

Among these micro-actuators, a piezoelectric or electrothermal actuator element acts also as an elastic flexure. Its stiffness adds to increase the natural frequency of micro-positioner systems. Yet, alternate activation of two such flexural micro-actuators generates a smaller stroke than a single microactuator does because the active one needs to overcome the in-active one. Some means of stroke magnification are useful to slider-level micro-positioner. Flexural bending helps unimorph produce a large stroke from small piezoelectric or thermal strains. For example, a U-shape piezoelectrically driven micro-positioner has two 1.8mm long piezoelectric unimorphs activated at $\pm 30\text{V}$ to produce a $1.04\mu\text{m}$ peak-to-peak displacement [7]. Shorter piezoelectric unimorphs produce a lesser stroke [8] but contributes to higher sway natural frequency. Level amplification, which is commonly adopted for the piezoelectrically actuated suspension, is however not effective to the slider-level micro-actuator given the small space.

A new kind of dual-stage micro-positioners have recently been developed based on thermal expansion of silicon or polymer [12-15]. Powerful thermal expansion of solids can deform silicon flexure of high rigidity. The kind of micro-positioner shows high system's natural frequency. Disadvantages of thermal actuations include high power requirement (for heating) and slow thermal response. Miniaturization helps reduce the power requirement and increase the thermal response speed. We have previously developed a lateral micro-positioner driven by thermal expansion of Si/SU8 composite [13-18]. The previous lateral design [14-15] can produce 50nm stroke at 1kHz activation while it shows a high natural frequency of up to 31kHz. A larger stroke is desired to cover more data tracks. However, a large thermal actuation is usually at the expense of reduced stiffness.

In this paper, we will present a rotary design of electro-thermally activated micro-positioner that addresses the need for a larger stroke, as much as 6-7 folds of the previous lateral design's [14-15]. This enhanced stroke generation is achieved by the lever amplification of rotated slider without requiring more power or compromising the high resonant frequency. Subsequent sections will present design, analyses, and characterization of the rotary micro-positioners.

Figure 1. (a) a schematic showing a slider-level dual-stage actuation scheme; (b)-(c) scanning electro-micrographs for head-gimbal assembly (left) with a micro-positioner (right) located at the gimbal tip to move a dummy femto slider.

2. Rotary Micro-positioner Design

Nowadays, femto sliders are adopted in hard disk drives as the read-write-head carrier, in replacement of Pico sliders. A femto slider, which is half the size of Pico slider, weighs 0.63mg. It has a size of 0.85mm long, 0.7mm wide and 0.23mm thick. In this study, we develop an electro-thermally activated rotary micro-positioner to move the femto slider. The target stroke requirement is at least 100nm while target natural frequency is above 20 kHz for the micro-positioner system carrying a femto slider.

Figure 1 shows the proposed and developed a rotary micro-positioner, which is adhesively bonded to a gimbal and in turn its stage carries a femto slider (also by adhesive bonding). This rotary stage is pivoted on a T-shape flexural hinge and flanked by two thermal unimorphs. Figure 2 shows that each thermal unimorph consists of a comb-shape silicon microfins and SU-8 expanders filled between the fin gaps. Activation of the thermal unimorph is by resistive heating through the integrated micro-heater. Polymeric thermal expansion bends the silicon backbone, while widening the silicon fin gaps. Figure 2d shows clockwise stage rotation upon activation of the left unimorph. Alternately, activation of the right unimorph drives the stage into a counter-clockwise rotation (see Figure 2e). The stage's position remains unaltered by ambient temperature change as the equal and opposite strokes cancel out.

This rotary micro-positioner is fabricated using high-aspect-ratio micromachining techniques [17-18]. Silicon micro-structures of 65 μ m high are obtained by silicon trenching using deep reactive ion etching (DRIE) technique. Solid polymer expanders are obtained by casting of liquid pre-polymer in silicon trenches, followed by lithography and post-baking. A complete micro-machined device of the micro-positioner is shown in Figure 1c.

Figure 2. Design of electro-thermally activated rotary micro-positioner: (a) its assembly with a femto slider; (b) a rotary stage and two thermal unimorphs; (c) the neutral position of the inactive micro-positioner; (d) clockwise rotation of the stage upon activation of the left unimorph; (e) counter-clockwise rotation of the stage upon activation of the right unimorph

Table I. Design parameters of a rotary micro-positioner

	Longitudinal dimensions	Transverse dimensions	Thickness
Unimorph's fin	$L_f=30\mu\text{m}$	$w_f=10\mu\text{m}$	$t=65\mu\text{m}$
Unimorph's backbone	$L_1=160\mu\text{m}$	$w_1=20\mu\text{m}$	$t=65\mu\text{m}$
Tiny beams at Unimorphs' tip	$L_2=40\mu\text{m}$	$w_2=15\mu\text{m}$	$t=65\mu\text{m}$
Pivotal tiny beams	$L_o=50\mu\text{m}$	$w_o=15\mu\text{m}$	$t=65\mu\text{m}$
Pivotal anchor	$L_a=280\mu\text{m}$	$w_a=100\mu\text{m}$	$t=65\mu\text{m}$
Stage's corner-to-corner distance	-	$W=400\mu\text{m}$	$t=65\mu\text{m}$
Offset between unimorph tip-pivot	$h=105\mu\text{m}$	-	$t=65\mu\text{m}$
U-shape Micro-heater	$L_h=195\mu\text{m}$	$w_h=5\mu\text{m}$	$t=0.2\mu\text{m}$

Table II. Material properties used in simulations

	Si	SU8	Pt	AlTiC
Young's modulus	132 GPa	3.2 GPa	168 GPa	380 GPa
Poisson's ratio	0.22	0.33	0.38	0.3
Density	2330 kg/m ³	1200 kg/m ³	2145 kg/m ³	4267 kg/m ³
Thermal expansion coefficient	$2.6\times 10^{-6}/\text{K}$	$55.8\times 10^{-6}/\text{K}$	$8.8\times 10^{-6}/\text{K}$	$7.9\times 10^{-6}/\text{K}$
Specific heat	702 J/kg-K	1200 J/kg-K	1300 J/kg-K	878 J/kg-K
Thermal conductivity	148W/m-K	0.2W/m-K	71.6W/m-K	20.0 W/m-K
Electrical resistivity at 25°C	0.02 $\Omega\cdot\text{m}$	0.2 $\Omega\cdot\text{m}$	$2.25\times 10^{-7}\Omega\cdot\text{m}$	-

3. Analytical Modelling

This section will present simple analytical models to estimate the electro-thermo-mechanical response of the micro-positioner. First, a pseudo-rigid-body model [19-20] is developed to calculate the stage's rotational stiffness and system's natural frequency. Second, a beam deflection theory is used to calculate the thermal unimorph's bending and the stage rotation. Third, a thermal circuit model is developed to predict the system's thermal time constant.

Rotational stiffness and system's natural frequency

This rotary stage is on the supports of multiple flexures (see Figure 3a-c). Though the stage design has a complex geometry, it can simply be modelled as pseudo rigid bodies and the stage rotation can be expressed in terms of a single degree of freedom θ . The pseudo-rigid-body model consists of a rigid-body stage pinned on a pivotal hinge with torsional stiffness $2k_o$, which represents the T-shape flexures. The two thermal unimorphs act also as flexures to support the rotary stage through a tiny cross beam each. A unimorph can be modelled as a vertical linkage of length L_1 pinned at the point A with a torsional spring of stiffness k_1 . The cross beam, which connects the unimorph tip B to the stage corner C, is modelled as a horizontal linkage of length L_2 with a torsional spring of stiffness k_2 at the point B. The stage corner C is offset from the pivot point O by a horizontal distance of $W/2$ and vertical distance h .

On the assumption of small displacement, the orthogonal rotations α and β (for the vertical and horizontal linkages respectively) yield the same displacements at the corner C during the stage rotation θ . As such the linkage rotations are related to the stage rotation following: $\alpha = h\theta/L_1$ and $\beta = W\theta/(2L_2)$.

The external moment M_o applied to rotate the flexural stage for angular displacement θ is balanced by the internal elastic moments, which sum up to be:

$$M_o = 2k_o\theta + 2k_1\alpha + 2k_2\beta \quad (\text{Eq. 1})$$

Hence, the total effective stiffness of this flexural rotary stage is

$$K_o = \frac{M_o}{\theta} = 2k_o + 2k_1\left(\frac{h}{L_1}\right) + 2k_2\left(\frac{W}{2L_2}\right) \quad (\text{Eq. 2})$$

According to the beam deflection under constant distributed moment [21], the equivalent torsional stiffness of a flexure of length L_i can be calculated as $k_i = 2EI_i/L_i$ where I_i is the second order moment of cross section area, E is the Young's modulus of flexure (made of silicon here). For simplicity, the unimorph's stiffness is estimated by its silicon backbone's, while the stiffness contribution by the laminated composite of Si/SU8 is neglected.

As for a second-order system [22], the natural frequency of the moving femto slider on this micro-positioner is:

$$f_n = \frac{1}{2\pi} \sqrt{\frac{2k_o + 2k_1(h/L_1) + 2k_2(W/2L_2)}{m(X^2 + Y^2)/12 + md^2}} \quad (\text{Eq. 3})$$

in which the slider has a mass $m=0.63\text{mg}$, length $Y=0.86\text{mm}$, width $X=0.7\text{mm}$, and zero distance d on the assumption that the slider's centre of gravity (CG) is collocated at the axis of rotation. Deviation of the slider's CG off the axis of rotation could increase the rotational inertia. Upon substitution the design parameters and silicon's material property (as listed in Tables I and II) in Equation 3, the system's natural frequency is estimated to be 24.4kHz, higher than the required 20kHz.

Figure 3. (a)-(c) A pseudo-rigid-body model for this rotary stage and (d)-(f) thermal unimorph and the thermally induced moment acting at its silicon backbone.

Unimorph bending and stage rotation

Timoshenko's theory for bimetals [23] was previously used to calculate the bending of thermal unimorph, which consists of comb-shape silicon micro-fins and polymer expanders [24-25]. Extension of this method, which was meant thin bi-metallic layers, requires tedious calculation of the effective properties for Si/SU8 composite [24-25]. Here, we develop an alternative method based on beam deflection as loaded by thermally induced moments (see Figure 3d-f).

When subjected to a uniform temperature rise ΔT , the polymer expands and induces the thermal stress $\sigma_{th} = E_{SU8} \alpha_{SU8} \Delta T$, as shown in Figure 3e. This induces an equivalent thermal blocked force $F_{th} = \sigma_{th} A$ acting on the fin walls of area $A = L_f t$ that confined it. In turn, a moment $M_{th} = F_{th} L_f / 2$ is induced thermally and it acts on the silicon backbone segment (see Figure 3f) where the fin and polymer expander are rooted. The backbone segment has a length of $s = 2w_f$, i.e. the sum of the fin width w_f and polymer spacing that is equal to the fin width for this design.

As such, the distributed moment acting on the silicon backbone of thermal unimorph is

$$m_{th} = \frac{\sigma_{th} A L_f t}{2s} = \frac{E_{SU8} \alpha_{SU8} \Delta T L_f^2 t}{4w_f} \quad (\text{Eq. 4})$$

According to the beam theory for uniform moment loading [21], the thermally induced tip displacement of the unimorph backbone is

$$u_{1,free} = \frac{m_{th} L_1^3}{3E_{Si} I_1} = \frac{E_{SU8} \alpha_{SU8} \Delta T L_f^2 t L_1^3}{12E_{Si} I_1 w_f}, \quad (\text{Eq. 5})$$

and the thermally induced tip rotation of the unimorph backbone is

$$\alpha_{free} = \frac{m_{th} L_1^2}{2E_{Si} I_1} = \frac{E_{SU8} \alpha_{SU8} \Delta T L_f^2 t L_1^2}{8E_{Si} I_1 w_f}. \quad (\text{Eq. 6})$$

As the active unimorph drives the rotary stage, its thermally induced moment needs to overcome the stage's total rotational stiffness K_o . Due to small contribution of unimorph stiffness, the thermally induced stage rotation θ is only a fraction of the unimorph rotation, following

$$\theta = \frac{M_{th}}{K_o} = \left(\frac{k_1}{K_o} \right) \alpha_{free}, \quad (\text{Eq. 7})$$

In turn, the femto slider is rotated following the stage and the slider's tip swings a displacement $u_s = Y\theta/2$ if the slider's center of gravity is located at the axis of rotation. The stroke ratio between the slider tip and the free unimorph tip is thus:

$$\text{Stroke ratio} = \frac{u_s}{u_{1,free}} = \left(\frac{Y}{2L_1} \right) \left(\frac{k_1}{K_o} \right) \quad (\text{Eq. 8})$$

This reveals that the rotated slider provides a factor of level amplification at $Y/2L_1$ to alleviate the stroke decrement due to the need for the active unimorph to overcome the stage's stiffness.

In this way, we can estimate performance of the present rotary micro-positioner, upon substituting the design and material parameters listed in Table I and II. Equation (5) estimates that a free stroke of $10.3\mu\text{m}$ upon 100°C heating of the active unimorph. This active unimorph can rotate the stage and induces a slider-tip displacement of $0.123\mu\text{m}$. This conservative estimate indicates that this design of rotary micro-positioner can meet the stroke requirement.

Thermal time constant

A thermal unimorph is activated by resistive heating. The heating power P depends on the voltage V across the integrated micro-heater of electric resistance R :

$$P = \frac{V^2}{R} \quad (\text{Eq. 9})$$

The average power of pulsed activation at the same voltage varies with the pulse's duty cycle [26]. Aside a small fraction used to raise the unimorph's temperature, a large portion of the heating is wasted and dissipated into the heat sink around the unimorph. Heat dissipation is mainly by conduction, through silicon microstructure of high thermal conductivity. Heat convection is however negligible due to the small device size and no underlying heat sink [14-15].

Figure 4. Heat path and temperature distribution across the micro-positioner during activation of left thermal unimorph: (left) Actual model with indicated heat path; (right) equivalent thermal circuit.

Temperature distribution over the unimorph is not uniform during resistive heating. The hottest spot of temperature T_h is roughly located at the middle of the silicon backbone on top of which the micro-heater resides. The silicon pad and frame remain as cool as the room temperature T_c . Figure 4 shows three paths of heat dissipation from the heat source to the heat sink: I) via the root of active unimorph;

II) via the middle pivot; III) via the inactive unimorph. An equivalent thermal circuit is developed to account for heat flow through the three paths, which have path thermal resistance $R_{th,I}$, $R_{th,II}$, and $R_{th,III}$ respectively.

The steady-state temperature rise due to the heating power P is thus

$$T_h - T_c = P \left[\frac{1}{R_{th,I}} + \frac{1}{R_{th,II}} + \frac{1}{R_{th,III}} \right]^{-1}. \quad (\text{Eq. 10})$$

Equivalent thermal resistance for each path is elaborated subsequently .

The thermal resistance for path I via the unimorph root is

$$R_{th,I} = R_{th,1/2} = \frac{L_1}{2\lambda A_1} \quad (\text{Eq. 11})$$

where the path length is $L_1/2$, λ is the thermal conductivity of silicon; $A_1 = w_1 t$ is the cross sectional areas of the silicon backbone, following Ref. [27].

The thermal resistance of the second heat path is a sum of thermal resistances for a few components, namely $R_{th,1/2}$ for distal half of the active unimorph, $R_{th,2}$ for the cross beam, $R_{th,O}$ for the pivotal beam, and $R_{th,a}$ for the extended anchor, following:

$$\begin{aligned} R_{th,II} &= R_{th,1/2} + R_{th,2} + R_{th,O} + R_{th,a} \\ &= 2 \left(\frac{L_1}{2\lambda A_1} \right) + \left(\frac{L_2}{2\lambda A_2} \right) + \left(\frac{L_O}{2\lambda A_O} \right) + \left(\frac{L_a}{2\lambda A_a} \right) \end{aligned} \quad (\text{Eq. 12})$$

Geometric dimensions are: the cross beam of a length L_2 and cross section area A_2 ; the pivotal beam of a length L_O and cross section area A_O ; the extended anchor of a length L_a and cross section area A_a .

The thermal resistance of the third heat path is contributed by those of half the active unimorph, two cross beams, and inactive unimorph, following

$$R_{th,III} = 3R_{th,1/2} + 2R_{th,2} = 3 \left(\frac{L_1}{2\lambda A_1} \right) + 2 \left(\frac{L_2}{2\lambda A_2} \right) \quad (\text{Eq. 13})$$

It is noted that the stage contributes to negligible thermal resistance as compared to other slender beams.

Heating of a thermal unimorph alone can be fast due to its small size and small thermal capacitance, which is the sum of various contributions from silicon backbone, silicon fins and SU-8 expander as follow:

$$C_u = \rho_{Si} c_{p,Si} L_1 A_1 + n (\rho_{Si} c_{p,Si} + \rho_{SU8} c_{p,SU8}) L_f A_f \quad (\text{Eq. 14})$$

where n is the number of the silicon fin and SU-8 expander unit, ρ and c_p denotes the density and specific heat and their subscript indicate the materials, either Si or SU8.

However, thermal response of the micro-positioner with integrated unimorph could be slower than the thermal unimorph alone. This happens because unintended heating occurs to the surrounding of the active unimorph. The heat affected zone has more gradual thermal gradient and contributes to extra thermal capacitance. Its thermal capacitance can be calculated as the total heat storage divided by the unimorph's average temperature rise. As a rule of thumb, twice the unimorph's thermal capacitance is taken for the heat affected zone.

As a first-order system for heating or cooling [28] , the system's thermal response time is:

$$\tau = \left[\frac{1}{R_{th,I}} + \frac{1}{R_{th,II}} + \frac{1}{R_{th,III}} \right]^{-1} (3C_u) \quad . \quad (\text{Eq. 15})$$

This equation suggests that miniaturization could make a thermal actuator respond faster. The present design of rotary micro-positioner is estimated with a 0.68ms time constant, upon substituting the design dimensions and material properties listed in Tables I and II respectively.

4. Finite Element Analysis

In addition, finite element analysis was performed to simulate the electro-thermo-mechanical response of micro-positioners. The models consist of 3D coupled-field solid finite elements (SOLID5 of ANSYS). The present simulation ignores heat convection, which was reported to be negligible for micro-device [14-15]. Figure 5 shows the simulated steady-state temperature distribution and thermo-elastic deformation of the micro-positioner under 4V resistive heating of one of the two thermal unimorphs. The simulation found that this rotary micro-positioner can rotate the slider with a 310.5nm slider-tip's displacement upon 4V activation of a 160 μm long thermal unimorphs. For comparison, we also simulated a lateral micro-positioner design whose design parameters are listed in Table III. The simulated stroke for the laterally actuated femto slider is 126nm at the 4V activation of a 120 μm long thermal unimorphs. In addition, the simulated deform shape reveals that translation of the lateral stage design could be slightly countered by the unintended stage rotation. In short, the simulation results show that the rotary design can produces 3-fold larger stroke than the lateral design, even at the about the same induced maximum temperature rise. This is attributed to lever amplification of rotated slider and 33% longer thermal unimorph in the rotary design.

Figure 5. Simulated deformed shape and temperature contour of the micro-positioner whose left unimorph is activated by 4V resistive heating: (a) the present rotary design and (b) the previous lateral design.

Table III. Design parameters of a lateral micro-positioner

	Longitudinal dimensions	Transverse dimensions	Thickness
Unimorph's fin	$L_f=30\mu\text{m}$	$w_f=10\mu\text{m}$	$t=65\mu\text{m}$
Unimorph's backbone	$L_1=120\mu\text{m}$	$w_1=25\mu\text{m}$	$t=65\mu\text{m}$
Flexure extended from unimorph's tip	$L_2=180\mu\text{m}$	$w_2=25\mu\text{m}$	$t=65\mu\text{m}$
Pivotal flexure	$L_o=100\mu\text{m}$	$w_o=20\mu\text{m}$	$t=65\mu\text{m}$
Pivotal anchor	$L_a=200\mu\text{m}$	$w_a=100\mu\text{m}$	$t=65\mu\text{m}$
Stage's corner-to-corner distance	-	$W=580\mu\text{m}$	$t=65\mu\text{m}$
U-shape Micro-heater	$L_h=175\mu\text{m}$	$w_h=5\mu\text{m}$	$t=0.2\mu\text{m}$

5. Experimental Set-up

Two types of micro-positioner devices are tested experimentally, namely the present rotary design and the previous lateral design. The devices under test were mounted on a printed circuit board (PCB) and their contact pads were wired bonded. A dummy femto slider was adhesively bonded on the stage of each device. Source meter is used to measure I-V curves of micro-heater integrated in the unimorphs of each micro-positioner. Various voltage waves were used to electro-thermally activate the micro-positioner. A square wave generated by a source meter was used to excite a step response. Two half-sine voltage signals of 180° phase difference and 50% duty cycle are fed to excite a harmonic response. A full-wave rectifier with Op-Amp was used to generate the two half-sine waves from its two channels. A dynamic signal analyser generates a swept sine wave and measure the frequency response of the micro-positioner. To remove ground noises during dynamic measurement, the device under test and LDV sensor head are mounted on a vibration isolation table as shown in Figure 6. An X-Y-Z stage is used to adjust the position of the device on PCB so that the sensor laser spot is aimed at the slider's tip. A laser Doppler vibrometer (Polytec OFV534) with 100nm/V sensitivity is used to measure the dynamic displacement of the slider on the activated micro-positioner.

Figure 6. Experimental setup for measuring the displacement of the moving slider on PCB

6. Results and Discussions

Micro-heaters for these two types of micro-positioners have roughly the same I-V curves, as shown in Figure 7. The measured micro-heater resistance is 50.4Ω for the rotary design, while it is 48.3 Ω for the lateral design. The micro-positioner moves the piggyback slider in step when one of its two unimorphs is activated by 4V square pulse. The slider's displacement rises with the pulse on but falls with the pulse off, like those for first-order system. Figure 8 shows that the rotary micro-positioner deliver a slider's static displacement of 310nm, which is 6 times larger than the 53nm induced by the lateral design, during the same 4V activation. This confirms that rotary design helps to amplify stroke generation at about the same power requirement of 222-223mW at 4V. However, the rotary design takes a longer time constant of 0.7ms to rise or fall, as compared to 0.5ms taken by the lateral design under the pulsed activation.

The micro-positioner can generate nearly harmonic motion when its two unimorphs are activated alternately by half-sine voltage waves of 50% duty cycle. In this way, the slider can be electrothermally moved in bi-directions (see Figure 9) just like the piezoelectrically driven slider. Figure 10 shows that thermally induced actuation depends strongly with driving frequency. For

example, the dynamic stroke amplitude (half of the peak-to-peak displacement) of the electro-thermally rotated slider decreases from 290nm at 500Hz to 153nm at 1000Hz. The stroke amplitude decays with increasing frequency because the activation time becomes shorter than that needed to fully raise the unimorph temperature. Yet, thermal activation can excite the moving slider into resonance, albeit at a much small stroke amplitude. Frequency response (in Figure 11) shows that the resonance of the rotary micro-positioner occurs at 35 kHz with resonant amplitude of a few nanometres. In addition, it is noted that the gain decay is -11dB/dec up to 1kHz driving frequency for the rotary micro-positioner. A cut-off frequency with 3dB decrement occurs at 250 Hz due to slower thermal response. After all, the rotary design of electro-thermally activated micro-positioner produce larger dynamic stroke as compared to the lateral design. But, the lateral design has a higher cut-off frequency of 370Hz despite have a slight lower mechanical resonant frequency at 31kHz. The decaying trend of dynamic thermal actuation appears similar to the dynamic amplitude decay of the rotary voice coil motor [29].

Figure 7. I-V Curves for the unimorphs' Pt micro-heater integrated in a rotary micro-positioner (red solid line) and a lateral micro-positioner (black dashed line). The decreasing gradient of I-V curve is due to positive thermal coefficient of electrical resistance.

Figure 8. The measured step responses for the micro-positioner, which swings a femto slider, upon 4V square-pulse activation of one of its two unimorphs. The square pulse supplied to the rotary micro-positioner has a 10ms pulse-width; whereas, that to the lateral micro-positioner has a 5ms pulse-width.

Figure 9. Harmonic responses of the moving slider on the micro-positioner upon alternate activation by half-sine wave of 50% duty cycle at (a) 500Hz and (b) 1kHz.

Figure 10. Peak-to-peak dynamic displacements of the moving slider against the harmonic frequency

Figure 11. Frequency responses of the moving slider on electro-thermally actuated micro-positioner

Table IV. Performance comparison among various slider-level micro-positioners

	Hirano et al [5] (IBM)	Jing et al [6] (SAE Magnetics)	Nojima et al [7] (Toshiba)	This work (NTU-DSI)
Actuator type (Actuator material)	Electrostatic (Ni comb)	Piezoelectric (PZT/SUS304)	Piezoelectric (PZT/SUS304)	Electro-thermal (SU8/Si)
Stage type	Rotary	Lateral	Rotary	Rotary
Slider (mass)	Pico Slider (1.8mg)	Pico Slider (1.8mg)	Femto Slider (0.63mg)	Femto Slider (0.63mg)
Footprint times Height	2.1mm×1.7mm ×0.2mm	2.5mm×1.2mm ×0.32mm	1.36mm×1.3mm ×0.3mm(estimate)	1.14mm×0.86mm ×0.065mm
Driving Voltage	30V±20Vsin ωt	+20Vsin ωt	20V±20Vsin ωt	4Vsin ωt
Displacement amplitude at 1kHz	300nm	504nm	80nm	153nm
Gain decay (displacement/V)	-40dB/dec	0dB/dec	0dB/dec	-11dB/dec
Resonant frequency	2.2kHz	12kHz	21.8kHz	35kHz

7. Comparison with Previous Works

Solid thermal expansion is known to be powerful, in terms of both thermal strain and thermal stress, but slow in macro scale. Miniaturization makes thermal micro-actuators fast to respond, at the expense of reduced stroke generation. These thermally actuated micro-positioner using the powerful thermal unimorph (0.12-0.16mm long) requires small foot print (slightly larger than the femto slider's footprint), and low driving voltage (less than 5V). This work shows that the rotated slider of the rotary micro-positioner helps magnify the thermally induced stroke, which is 6-7 times higher than that generated by the lateral design. In addition, the rotary micro-positioner achieved a very high resonant frequency of 35 kHz for moving a femto slider.

Table IV compares the present electro-thermal micro-positioner with the other reported micro-positioners, in terms of principle, design, and performance for moving a slider. In comparison, the weaker electrostatic actuator requires twice the footprint of pico slider; the piezoelectric actuated micro-positioner requires a longer unimorph (1.2-1.8mm long) to magnify the small piezoelectric strain. The increased flexibility of the piezoelectric unimorph is at the expense of reduced system's natural frequency for moving slider. Weakness of thermal actuation is attributed to low thermal cut-off frequency and the decay of dynamic stroke.

8. Conclusions

This experimental investigations show that the rotary design of electro-thermally activated micro-positioner can produce 6-7 times larger stroke at the slider tip than the previous lateral design does. Slider rotation in the rotary design helps to magnify the thermally induced stroke. Such stroke magnification does not require more power to activate the thermal unimorph. In addition, the rotary micro-positioner has a 35kHz sway resonant frequency, higher than 31kHz of the previous lateral design. The weakness of this rotary micro-positioner is attributed to the low cut-off frequency and the gain decay. Further miniaturization of the thermal unimorph design is anticipated to improve the speed of thermal micro-actuation.

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