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Fast response thermal linear motor with reduced power consumption

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Abstract

This paper presents the principle, fabrication and characterization of a fast response Thermal Linear Motor (TLM) having reduced heat loss (and thus power consumption) without reduction in mechanical output power. Our double wedge shaped, aluminum TLM is 12 $\mu$m and 6 $\mu$m wide at the edges respectively center and 400 $\mu$m long. Theory and measurements show that this TLM has up to 20\% more mechanical output power for the same electrical input power compared to a simple rectangular beam TLM. The TLM is the crucial driving element for our Hard Disk Drive (HDD) thermal micro actuator. The actuator uses two of the here presented TLMs to accurately move the HDD head up to several micrometers.

Keywords: Thermal actuation, Optimization, HDD, Thermal Linear Motor, Nanopositioner

1. Introduction

Hard Disk Drives (HDD) are used for sustainable digital storage in different applications like computers, and MP3-players. Currently, conventional HDD cost 5 to 10 times less per GigaByte than their flash based competitors. Future drives will use narrower tracks, to increase capacity without increasing costs. Narrower tracks require higher tracking accuracy. Increasing the tracking accuracy by increasing the servo bandwidth is limited by the destabilizing effect of the mechanical resonance in the actuator arm. This can be solved by using a dual-stage actuator, in which the positioning is split in a coarse- and a fine-stage. The fine-stage has a relatively high bandwidth, improving accuracy and seek time.

The smaller the fine-stage actuator, the higher the bandwidth and the accuracy of the positioning system can be. Therefore different Micro Electro-Mechanical System (MEMS) fine-stage actuators have been developed (e.g. [1]). These actuators are generally based on electro-static actuation which is fast and has low power consumption, but generates only small forces and uses small air gaps & electrodes.

We are working on a thermally actuated fine-stage actuator which has the same or higher driving force than an electrostatic actuator. The actuator is targeted to reach 3 to 5 kHz bandwidth for a positioning accuracy better than 5nm. The concept of the thermal actuator is shown in Fig. 1. The actuator uses two Thermal Linear Motors (TLMs) and can displace the HDD head by several micrometers. Our TLMs are made of aluminum because it has good...
thermal properties [2].

The HDD application requires a TLM with a low time constant (<< 1 ms) and optimize power consumption, in order to minimize the heat production in the HDD. Optimized thermal actuators, for example [3, 4], improve the stroke versus power consumption by reducing the actuator width at the edges to lower the heat loss to the frame. This shape negatively impacts the dynamic performance, as we previously presented in [5], and is therefore unsuitable for the HDD actuator. In this paper we present a wedge shaped TLM which reduces power consumption without loss in dynamic performance.

2. Simulations

In its simplest form the TLM is a beam made from a single material. The presented TLM has a wedge shaped beam, see fig 2. The beam is connected on one side to the fixed world (e.g. frame) and the other side to a moving part, like the rotating platform in the HDD actuator. The TLM is joule heated by passing an electrical current through it. In the aluminum TLM the maximum temperature should typically be kept below 200°C. Both the analytical model and Finite Element Model (FEM) of the rectangular TLM have been previously introduced in [5]. Increasing the width at the edges (fig. 2a) improves the heat transfer to the surroundings, and thus reduces the thermal lag. On the other hand, reducing the width at the edges (fig. 2b) lowers the power consumption. Our FEM of the wedge shaped TLM allows us to vary its dimensions to study the performance of different configurations.

To compare motors with different designs, and for shape optimization in general, a definition of optimal is required. Since the TLM cannot be actively cooled, it continuously consumes power to remain at a nominal temperature for bi-directional operation. The optimal TLM delivers the required mechanical power at the lowest nominal power consumption. Therefore, the Performance Index (PI) we use is the ratio of the maximum mechanical power a motor can generate (during cooling) \( P_{m,\text{max}} \) and the nominal input power \( P_e \):

\[
PI = \frac{P_{m,\text{max}}}{P_e} = \frac{F_0 \cdot x_0}{T \cdot V T} \quad [5]
\]

The ideal wedge ratio (ratio of the width at the center and at the edge) is between 0.3 and 0.4, boosting performance by 20% compared to a rectangular shaped TLM (wedge ration 1), see fig 3. On the other hand, if the width at the center is larger than at the edges, performance can drop by more then 20%.
Fig. 2: Layout of the wedge shaped TLM, (a) \(w_c < w_e\), (b) \(w_c > w_e\). The wedge ratio is defined as \(w_c / w_e\).

Fig. 3. The performance index, defined as mechanical power divided over electrical power, versus the width to length ratio. The performance is maximal when the center width is 30 to 40% of the edge width.

3. Realization

To validate the simulation results special test structures to measure the mechanical power of different TLM designs were realized (fig. 4). The TLMs are made on a silicon substrate and have a 100 nm thin aluminum heater isolated by two 100 nm thin layers of silicon dioxide. The heater is sandwiched between two 2.5 μm thick sputtered aluminum layers. These are dry etched to form the body of the TLMs. The TLMs are released from the backside using a combination of wet and dry etching. This process allows us to fabricate TLMs that are directly connected to springs with separate heaters. The self-heated springs are necessary to measure the force without influencing the temperature profile of the TLM.

The displacement and time constant are measured directly for each type of TLM. The TLMs are employed in a V-beam configuration to convert the small thermal expansion into micrometer displacements that can be measured using a commercial vision system (Polytec MSA-400). The temperature increase is measured in the rectangular shaped TLM and used as the base line for the comparison. The other TLMs are calibrated using the heater of the force measurement spring as temperature sensor. This way the maximum temperature, which is typically limited for safety reasons, is the same in all the devices.

Fig. 4 shows the two test structures for the TLM which is wider at the edges than at the centre, and also the test structures for opposite design (better for quasi-static operation). The two test devices for the rectangular TLM are comparable and all motors have the same average width. Two thin beams are used instead of one thick beam to reduce the bending stiffness of the V-beam actuator.

4. Results and discussion

The results of displacement, time constant and force measurements for the three different designs are summarized in table 1 and an example displacement measurement is shown in fig. 5. It is not possible to directly measure the force, but since all devices have been fabricated on the same wafer the variations in the stiffness of the reference spring will be small. Therefore the force can be estimated by the displacement of the TLM with reference spring. As expected the design with reduced heat loss \((w_c > w_e)\) has the largest displacement and time constant. The design with increased heat loss \((w_c < w_e)\) is the fastest and has the highest performance (PI) as predicted by the simulations. However, the measured difference is smaller than predicted. This difference will be further studied, but is most likely due to the influence of the wedge shape on the bending stiffness of the V-beam actuator.
Fig. 4: SEM Photographs of the realized test structures to measure the mechanical output of the wedge shaped TLM. Left actuators $w_c < w_e$; Right actuators $w_c > w_e$. The springs attached to the outer actuators are for force measurement. Close up: the presence of the embedded heater is visible in the top surface of the spring / beams.

Table 1. Summary of the displacement, time constant and force measurements. The PI is normalized to the rectangular TLM.

<table>
<thead>
<tr>
<th></th>
<th>Rectangular TLM</th>
<th>Wedge shaped TLM $w_c &lt; w_e$</th>
<th>Wedge shaped TLM $w_c &gt; w_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement (µm)</td>
<td>3.01</td>
<td>2.99</td>
<td>3.40</td>
</tr>
<tr>
<td>Time constant (ms)</td>
<td>0.34</td>
<td>0.26</td>
<td>0.38</td>
</tr>
<tr>
<td>Force displacement (µm)</td>
<td>0.95</td>
<td>0.75</td>
<td>0.31</td>
</tr>
<tr>
<td>Power consumption (mW)</td>
<td>76.3</td>
<td>65.7</td>
<td>70.5</td>
</tr>
<tr>
<td>Normalized PI (to rectangular TLM)</td>
<td>-</td>
<td>+6%</td>
<td>-64%</td>
</tr>
</tbody>
</table>

5. Conclusion and future work

We have shown that our double wedge shaped TLM has a 6% better mechanical over electrical power ratio (PI) than a simple rectangular TLM. This means that the presented TLM delivers the same level of dynamic performance at lower power consumption. Also, we have shown that reducing the width of a thermal actuator at its edges to reduce heat loss, and thus power consumption, leads to reduced dynamic performance; 64% reduction in our case. The influence of the V-beam configuration on the dynamic performance will be studied further.

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References