

# A 'Millipede' scanner model

## Energy consumption and performance

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### 1 Summary

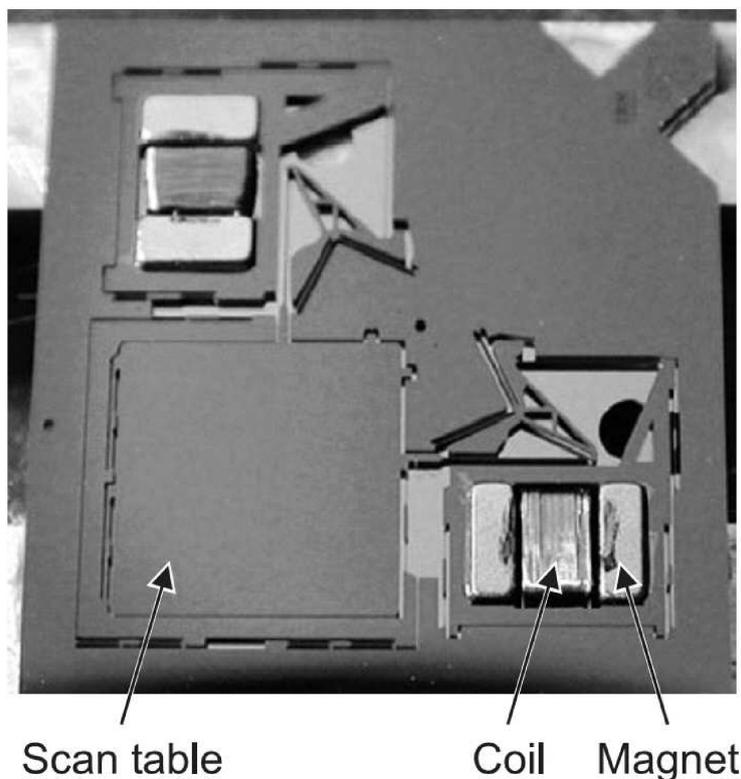
This short report (1) describes an energy model for the seek and read/write operations in a mass-balanced XY-scanner for parallel-probe storage by IBM [1] and (2) updates the settings of the MEMS model in DiskSim with recent published figures from this XY-scanner. To speedup system simulations, a straight forward second-order model is used without control loop. Read/write operation is modeled by quasi-static calculations. To approximate seek behavior, 'bang-bang' control is assumed; the result is close to the actual behavior with control loop [2]. Unfortunately, no energy measurements were available to validate the model. Using the proposed energy model, we are able to study the energy consumption of a MEMS-based storage device for different application areas and file systems.

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### 2 Modeling the voice-coil actuator

IBM's XY-scanner (which carries the storage medium) uses the electromagnetic force from a coil and a permanent magnet to drive its scan table. The generated force is linearly proportional to the applied current. The scan-table is suspended by springs that generate a counterforce, so for a certain applied current there is an equilibrium displacement. The coupling between the X- and Y-axis is very small [1] and is neglected in order to separate the scanner's behavior in the X- and Y-directions. This way each axis can be modeled separately by a one-dimensional spring-damper-mass model. The model is drawn in Figure 2.

The values of all the parameters except the damping coefficient are taken from [1] and are shown in Table 1. A Q-factor of approximately 8 is reported, from which the damping coefficient was determined ( $Q = \sqrt{km}/R_{\text{air}}$ ). Note that these values are of a single device instead of averages over a large volume of devices; especially the spring constants are very sensitive to small variations during fabrication. From private communication, it seemed that the values reported here are close to the worst-case scenario.



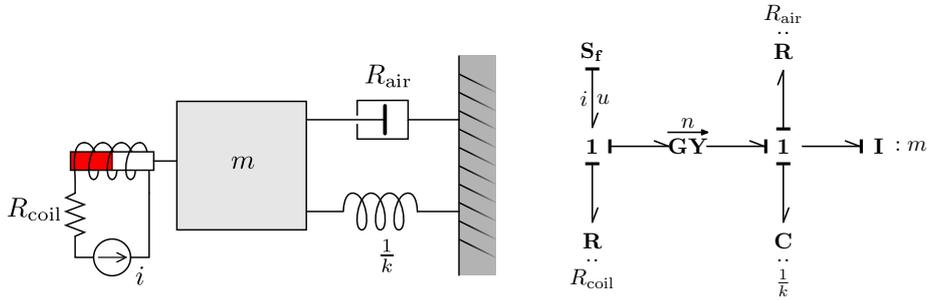
*Figure 1: Picture of IBM's voice-coil actuator (image copied from [1]).*

Because no control loop is present, this model can only be reliably operated at frequencies well below the resonant frequency. This means that the model cannot be used for actual seek performance and energy consumption. For seek operations a 'bang-bang' control approximation is used, whose result agrees well with measurement results from IBM. Because the damping is very small, ringing effects are considerable at actuation frequencies close to the resonant frequency. The resonant frequency lies around 150 Hz for both axes [1]. If we limit the simulations to a 10 Hz triangle for the scanning axis, ringing effects are small; the reading speed at 10 Hz equals 1 mm/s, which equals to 40 kbps per probe at a data density of 1 Tbit/in<sup>2</sup> (25 nm bit pitch). Also note that because an ideal current source is used, the resistance of the coil ( $R_{\text{coil}}$ ) does not show up in the dynamics of the model.

### 3 Time performance model

Because the read/write scan velocity is constant, the time to read or write a certain number of bits  $N$  at a given bit density  $d_{\text{bit}}$  is easily calculated using the following equation:

$$t_{\text{transfer}}(N) = \frac{N \cdot d_{\text{bit}}}{v_{\text{read}}} \quad (1)$$



**Figure 2:** Mechanical model of IBM's voice-coil actuator and the bond-graph of the spring-damper-mass model of one axis.

Parameter	Value	
$R_{\text{coil}}$	8.4	$\Omega$
$k_x$	104	$\text{N} \cdot \text{m}^{-1}$
$k_y$	91	$\text{N} \cdot \text{m}^{-1}$
$m_x$	$102 \cdot 10^{-6}$	kg
$m_y$	$82 \cdot 10^{-6}$	kg
$n_x$	$62 \cdot 10^{-3}$	$\text{N} \cdot \text{A}^{-1}$
$n_y$	$55 \cdot 10^{-3}$	$\text{N} \cdot \text{A}^{-1}$
$R_{\text{air}}$	$1 \cdot 10^{-2}$	$\text{N} \cdot \text{s} \cdot \text{m}^{-1}$

**Table 1:** Values from actuator published in [1]. See also figure 2.

Seek operations can't be simulated accurately with our simple model without control loop, which makes it difficult to calculate the exact seek time. However, it is possible to calculate the best possible seek time from the maximum possible acceleration; this will give a lower bound on the seek time  $t_{\text{seek}}$ . This calculation assumes maximum actuator force during the seek (first accelerating, then decelerating); in our case this maximum force is constant (the maximum current is limited). This so-called 'bang bang' control is time-optimal. Measurements performed by IBM indicate that the used control loop is able to approximate the ideal time-optimal performance [2].

DiskSim calculates the 'bang bang' seek time using a piecewise approximation, described in [3]. An analytical solution is described in [4], which is not repeated here for brevity. See figure 4 for the result for a seek from (0,0).

### 3.1 Time performance model in DiskSim

DiskSim calculates the time a probe takes to read/write a number of bits based on the per-probe data rate as shown in Equation (1).

Two seek models exist in DiskSim: (1) a single-parameter model and a (2) bang-bang model; Madhyastha et al. [5] give a detailed comparison of both models. Schlosser calculates the 'bang bang' seek time using a piecewise approximation, described in [3]. Hong et al. [4] propose and implement an analytical solution is described in [4]. Figure 4 (top) shows the seek time when seeking from the center (0,0) to any position within a probe storage field.

The standard MEMS model in DiskSim uses the same model for the time

performance as described above. It is therefore easy to provide input parameters for DiskSim. In Table 2, DiskSim's parameters are listed together with the values from our model.

Parameter	Value	Unit
Sled movement X	$d_{\max}$	nm
Sled movement Y	$d_{\max}$	nm
Bit cell length	$d_{\text{bit}}$	nm
Sled acceleration X	$\frac{F_{x,\max}}{m_x} = \frac{i_{\max} \cdot n_x}{m_x}$	$\text{m} \cdot \text{s}^{-2}$
Sled acceleration Y	$\frac{F_{y,\max}}{m_y} = \frac{i_{\max} \cdot n_y}{m_y}$	$\text{m} \cdot \text{s}^{-2}$
Sled access speed	$\frac{d_{\text{bit}}}{v_{\text{read}}}$	bps
Sled resonant frequency		Hz
Settling time constants	0	
Spring constant factor	$\frac{d_{\max} \cdot k_x}{i_{\max} \cdot n_x}$	

**Table 2:** Values for the parameters in DiskSim's MEMS model. Refer to [3] for details about the parameters.

$d_{\max}$  and  $i_{\max}$  are the same for the X and Y direction and are  $50 \mu\text{m}$  and  $200 \text{ mA}$  respectively. The size of a bit  $d_{\text{bit}}$  equals  $25 \text{ nm}^2$  <sup>1</sup>. The ratios  $\frac{k_x}{k_y}$  and  $\frac{n_x}{n_y}$  are almost equal, which means that DiskSim's 'spring constant factors' in both X and Y directions are almost equal. It is therefore not needed to adjust DiskSim for separate X and Y spring constant factors.

## 4 Energy model

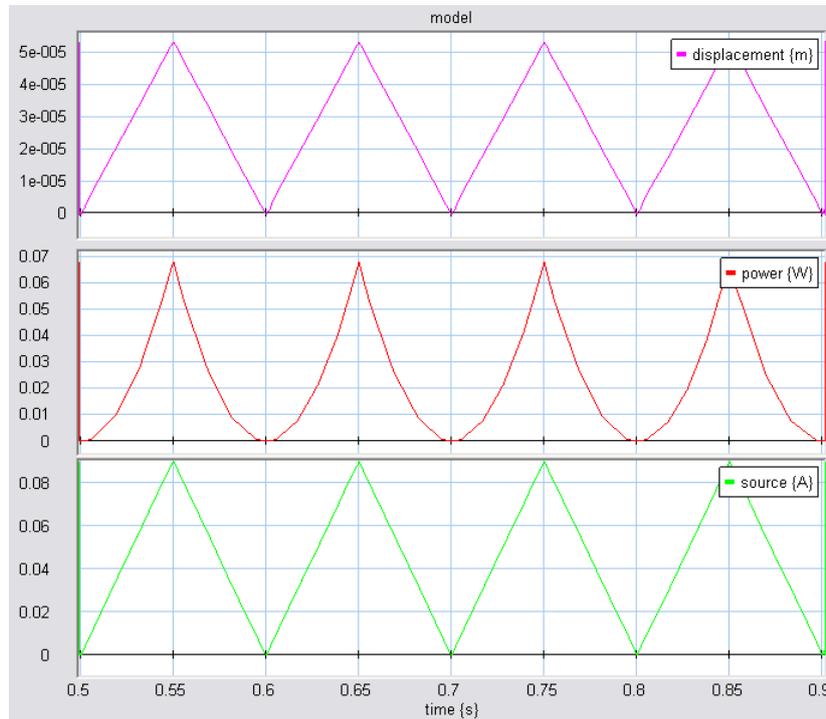
During read/write and standing still, the velocity is constant and the scanner behaves quasi-static. As a result, the dynamics of the model can be left out, which makes power estimation much easier. It is found that the resistance of the coils account for almost all energy loss. The equivalent current needed to overcome the air's viscous drag force while moving at  $1 \text{ mm/s}$  is  $0.2 \text{ mA}$ , which is two orders of magnitude lower than the average current needed to push against the springs. Therefore, we have neglected this air damping; however for larger read speeds, the damping by air should be taken into account. The actuator is driven by a controlled current source that is set to the current that is needed to hold the actuator in equilibrium at a certain position; this is stated in equation (2). The voltage across the power supply is given in equation (3). Because we neglect  $\frac{d(\text{pos})}{dt}$  at low frequencies, the power can be calculated with equation (4).

$$i = \frac{k}{n}(\text{pos}) \quad (2)$$

$$u = iR_{\text{coil}} + n \cdot \frac{d(\text{pos})}{dt} \quad (3)$$

$$p = \frac{k^2 R_{\text{coil}}}{n^2} (\text{pos})^2 + k \cdot (\text{pos}) \frac{d(\text{pos})}{dt} \cong \frac{k^2 R_{\text{coil}}}{n^2} (\text{pos})^2 \quad (4)$$

<sup>1</sup>The square bits is a simplification. In later experiments, the length of a bit in the read/write direction is larger than the length in the other direction (track pitch).



**Figure 3:** A simulation of the model showing the power consumption during a triangular scan, for one actuation direction. The power's quadratic dependence on the position is clearly seen.

In Figure 3, the result of a simulation is shown, where the actuation current is ramped up and down to simulate e.g. reading back and forth. The actual displacement closely follows the actuation current, except for slight deviations around the turning points. The power curve's quadratic dependence on the displacement is clearly seen, which confirms equation (5). The area below the power curve equals the consumed energy (equation (12)).

In contrast to the read/write energy model, the seek model cannot factor out the dynamics of the system. Yet, when assuming 'bang-bang' control, the applied current is constant (at maximum allowed current) during the seek. The seek energy is then easy to estimate, since a constant (maximum) power is dissipated. Comparison with measured current graphs [2] shows that this approximation is within 20% of reality. Figure 4 (bottom) shows the seek energy when seeking from the center (0,0) to any position within a probe storage field.

#### 4.1 Calculation of energy consumption for 3 modes

With equation (4) we can calculate the energy consumption of the modes in which the actuator can be put. Three modes were chosen: standing still on a certain location (*idling*), moving at a constant velocity (*reading/writing*) and going to a certain location as fast as possible (*seeking*).

1. Rest = staying at location  $\mathbf{r} = (r_x, r_y)$  for time  $t$ :

$$E_{\text{stay}}(\mathbf{r}, t) = R_{\text{coil}} \left[ \left( \frac{k_x r_x}{n_x} \right)^2 + \left( \frac{k_y r_y}{n_y} \right)^2 \right] \cdot t \quad (5)$$

2. Reading/writing = moving from  $x_1$  to  $x_2$  at velocity  $v = v_{\text{read}}$ :

The acceleration phase to reach the read velocity  $v$  is not taken into account. Because dynamics are neglected, moving from  $x_1$  to  $x_2$  consumes the same amount of energy as moving from  $x_2$  to  $x_1$  (at the same fixed velocity). Therefore, the following calculation assumes that  $x_1 < x_2$ , if this is not the case  $x_1$  and  $x_2$  should be swapped to obtain the correct energy consumption. Also note that the same formulas hold for movement in the  $y$ -direction.

$$t_2 = \frac{x_2 - x_1}{v_x} \quad (6)$$

$$x(t) = x_1 + t \cdot v_x, \quad t \in [0, t_2] \quad (7)$$

$$E_{\text{move},x}(x_1, x_2, v_x) = \int_0^{t_2} p(x(t))|_{y=0} dt \quad (8)$$

$$= \int_0^{t_2} \frac{k_x^2 R_{\text{coil}}}{n_x^2} x^2(t) dt \quad (9)$$

$$= \frac{k_x^2 R_{\text{coil}}}{n_x^2} \cdot \left[ \frac{1}{3v_x} (x_1 + t \cdot v_x)^3 \right]_0^{t_2} \quad (10)$$

$$= \frac{k_x^2 R_{\text{coil}}}{3v_x n_x^2} \cdot (x_2^3 - x_1^3) \quad (11)$$

The total energy consumed during a read operation will be the sum of  $E_{\text{move},x}$  and  $E_{\text{stay},y}$ :

$$E_{\text{read},x}(x_1, x_2, v_x, y) = E_{\text{move},x}(x_1, x_2, v_x) + E_{\text{stay}} \left( (0, y), \frac{x_2 - x_1}{v_x} \right) \quad (12)$$

3. Seeking = jumping from  $\mathbf{r}$  to location  $\mathbf{q}$  (see text for discussion):

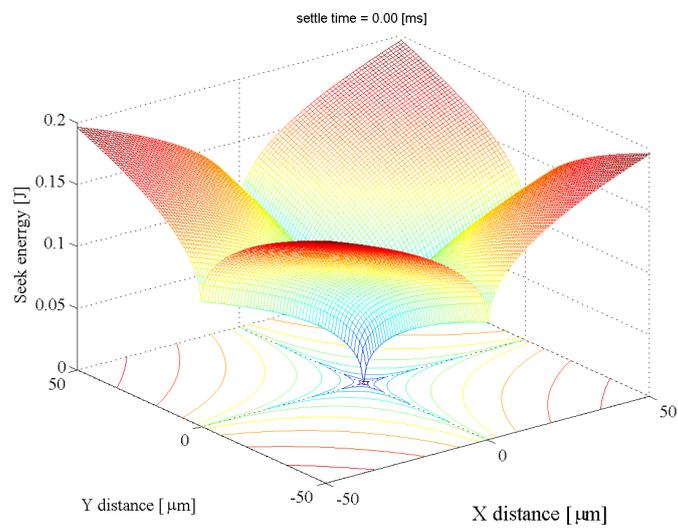
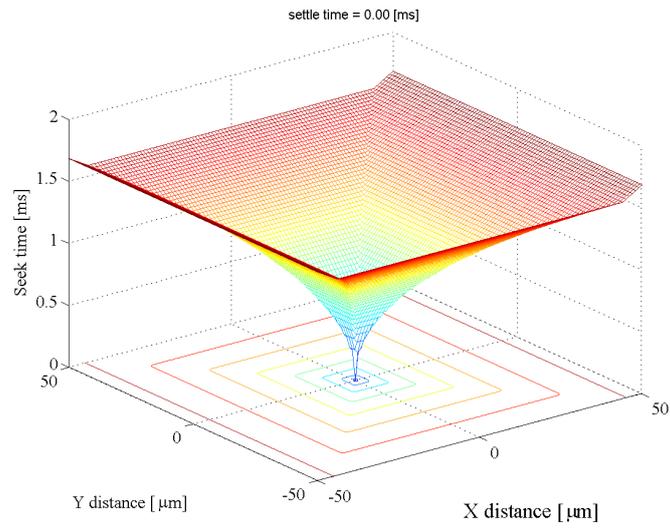
$$E_{\text{seek}}(\mathbf{r}, \mathbf{q}) = i_{\text{max}}^2 R_{\text{coil}} \cdot (t_{\text{seek},x} + t_{\text{seek},y}) + E_{\text{stay}} \left( (q_x, 0), t_{\text{seek},y} - t_{\text{seek},x} \right) \quad (13)$$

Because 'bang bang' control is used, the power consumption is constant during a seek, and is equal to the power consumption with maximum applied current. Note that this does not include settling time. During settling, the power consumption is much lower, because much smaller currents are used (and  $p \propto i^2$ ), which is why it is left out of the equation. During a seek, generally it will take an unequal amount of time to seek in the X and Y direction. Therefore in one of the directions, an additional stay energy must be added for the seek in the other direction to complete. In equation (13), it was assumed that the seek in X direction would be shorter than in the Y direction.

See figure 4 for the result for a seek from (0,0).

## **4.2 MEMS energy model in DiskSim**

The standard MEMS model in DiskSim calculates the energy consumption by assuming a constant active power and idle power. However, this is inaccurate for the electromagnetically actuated XY-scanner by IBM. Therefore, we modified DiskSim to accommodate the analytical energy models presented in this report.



**Figure 4:** Model results: the seek time and energy of a seek from (0,0) to an arbitrary position.

## References

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