

ME1633: Integration of Physics, Motion and Metrology

Assignment 4: Magnetism

22 November 2013

- You can do this assignment on your own or in groups, as long as you hand in your own solutions and it becomes clear that you understand your solutions. Formulate your solutions step-by-step, carefully pointing out the logical structure of your answer, but keep your answers brief.
- *Only for the students who follow the PME track's course ME1633:* Your solution to this assignment must be submitted in the lecture or via Blackboard in pdf format *before* 4 December 2013, 23:59h.
- If in some question you happen to need an answer from a previous question that you don't know the answer to, assume an answer or at least explain the method you would use when you would have had that previous answer.
- Your solution must be formulated in English.
- Contact: (Problem 1-2) Murali K Ghatkesar (m.k.ghatkesar@tudelft.nl); Office hours (G-1-400): Tuesdays and Fridays between 12:30h and 14:00h or (Problem 3-5): Oscar van de Ven (F-2-330; o.s.vandeven@tudelft.nl)

Problem 1

(20 points)

In the experimental setup shown in Figure 1, a source at Q emits electrons by thermionic emission from a heated filament. At point R, the electrons shall have a velocity of $v_0 = 4 \times 10^7$ m/s along the x-axis and enter the face centre of a cubic box. The edges of the box are 0.6 m long each. The sidewalls are formed by metal plates, which are electrically isolated against each other. There is a small hole in some of the plates (at the points R,S,T indicated in the sketch above). Inside the box homogeneous magnetic and electrical fields can be generated such that their respective field lines are parallel to the edges of the box. The whole experiment is set-up in vacuum.

- (2p) **1a.** Calculate the electric potential required to accelerate the electrons from rest to v_0 (from Q to R in Figure 1).
- (4p) **1b.** In the following experiment, there are simultaneously both non-vanishing magnetic and electrical fields present inside the cube ($\mathbf{E} \neq 0$; $\mathbf{B} \neq 0$). The electrons enter the box again at R with v_0 and leave at S with the same velocity. There are two field configurations possible to achieve this. Explain one solution how the fields have to be oriented in order to accomplish this. Which criterion do you select to define the respective strengths?

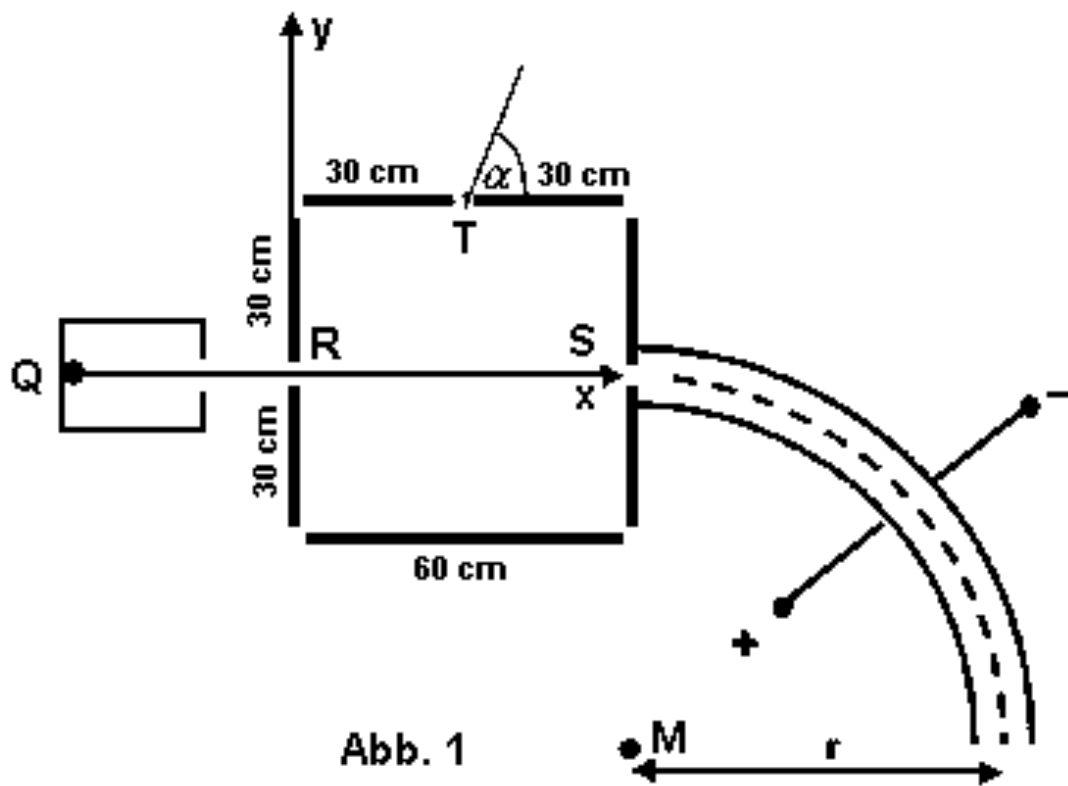


Figure 1: Wien Filter

- (3p) **1c.** An electrical potential of 1.5kV is applied to the condenser formed by two sidewalls of the cube. Calculate the electrical and magnetic field strength required to meet the conditions outlined in **1b**.
- (2p) **1d.** Only static magnetic field is present in the next experiment configuration. The electron beam must again be rectilinear between R and S. For which B-field is this possible? What is the influence on the speed of the electrons? Motivate your answer.
- (5p) **1e.** In the final experiments there is either a magnetic or an electric field inside the cube. The electrons shall leave the cube at T. There are two different situations observed. The electrons either leave under i) $\alpha_1 = 90^\circ$ or ii) $\alpha_2 < 90^\circ$. Explain how these two cases can be produced. Calculate the magnitude of the field strengths for the case where there is only an electrical field. iii) What is the speed of the electron in the two cases?
- (4p) **1f.** The electrons leave the cube in S again having a velocity v_0 . They then enter a circularly curved condenser (see figure 1). The electrical field strength is such that the electrons follow the dashed line. The field strength on the trace is 6.0 kV/m. Calculate the radius of curvature.

Problem 2

(20 points)

- (4p) **2a.** In the class, you have seen that magnet dropped through a metal tube took more time to reach the other side compared to the magnet dropped through a plastic tube. Explain why?
- (4p) **2b.** If a metal wire loop was wound on the plastic tube. Make a graph of the magnetic flux through the loop and current induced in the loop as a function of time. Explain your graph. Indicate different time points on your plot and any assumptions made.
- (6p) **2c.** Propose a method to determine acceleration due to gravity using a plastic tube, metal wire and the data of induced current in a loop.
- (6p) **2d.** Magnetic field strengths can be measured by a rotating coil gaussmeter. This device uses a small multi-turn coil rotating at a high speed on an axis perpendicular to the magnetic field. This coil is connected to an ac voltmeter by means of slip rings, like those shown in the **Figure 2**. In one specific design, the rotating coil has 400 turns and an area of 1.40 cm². The coil rotates at 180 rev/min. If the magnetic field strength is 0.450 T, find the maximum induced emf in the coil and the orientation of the normal to the plane of the coil relative to the field for which this maximum induced emf occurs.

Introduction to the HDD actuator

The hard disk drive (HDD), introduced by IBM in 1956, is still a cost-effective way of storing digital data. Therefore this mechanical way of storing data remains popular. An HDD consists of one or more rigid ('hard') rapidly rotating disks (platters) with magnetic heads arranged on a moving actuator arm to read and write data to the surfaces.¹ In this assignment we will study the magnetic actuator that rotates the arm around a pivot point. This arm is indicated in the left picture in Figure 3.

¹http://en.wikipedia.org/wiki/Hard_disk_drive

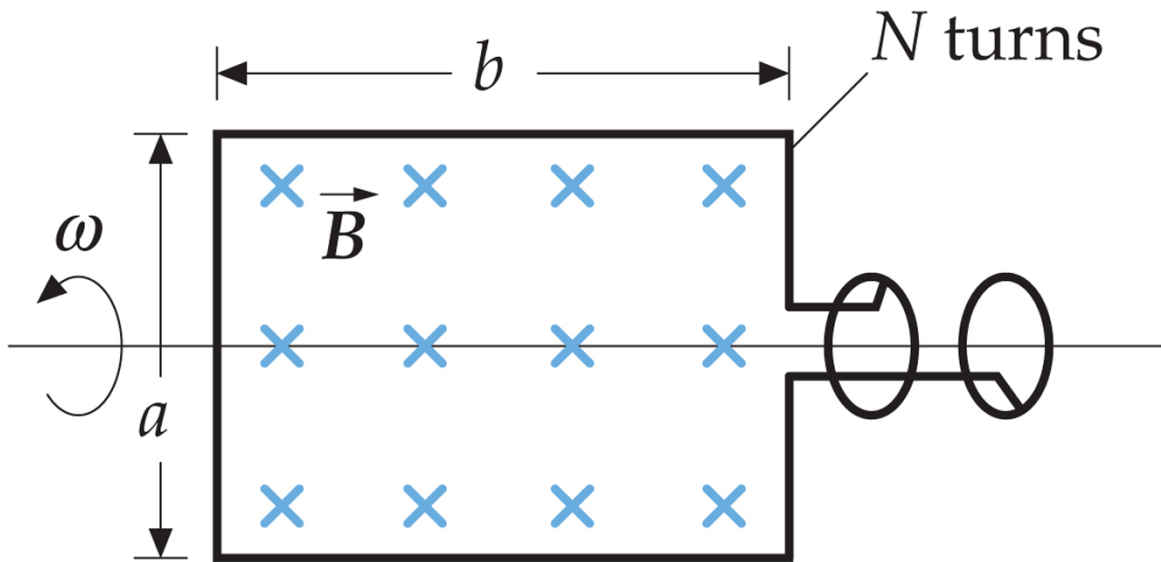


Figure 2: Rotating Coil Gaussmeter

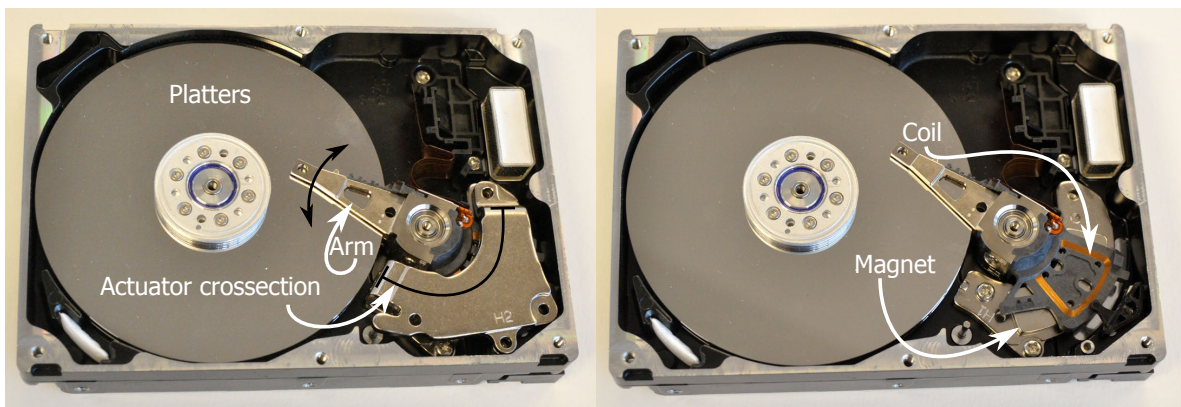


Figure 3: A harddisk with the cover off showing the head actuator (left). In the right picture one of the magnets is removed to uncover the coil. The indicated cross-section is schematically shown in Figure 4.

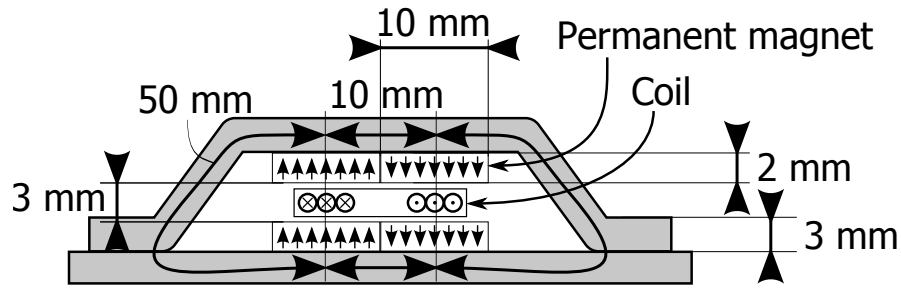


Figure 4: Actuator schematic. The coil (the wires in the different directions are indicated by \otimes and \odot) is supposed to move in horizontal direction, and is suspended in the other directions. Small arrows indicate the magnetization direction of the permanent magnets. The relevant dimensions are indicated in the drawing and in Table 1.

Table 1: Properties of the hard disk actuator.

Property	Value
Depth (orthogonal to the drawing) (d)	10 mm
Magnet width (horizontal) (w_m)	10 mm
Magnet thickness (vertical) (t_m)	2 mm
Air-gap thickness (vertical) (t_{air})	3 mm
Core length left & right (horizontal & vertical) ($l_{c,lr}$)	50 mm
Core length top & bottom (horizontal) ($l_{c,tb}$)	10 mm
Core thickness (horizontal & vertical) (t_c)	3 mm
Magnet remanent flux density (B_r)	1.35 T
Core relative permeability ($\mu_{r,core}$)	4000
Air relative permeability ($\mu_{r,air}$)	1
Magnet relative permeability ($\mu_{r,m}$)	1

To analyze the magnetic actuator we will assume that the system can be represented by the 2-dimensional schematic shown in Figure 4, this can be seen as the cross-section indicated in Figure 3. The numeric values for the relevant properties are listed in Table 1.

Problem 3: Hard-disk-arm traction

(8 points)

- (3p) **3a.** Which of the basic electromagnetic principles of actuation generates the rotational motion of the arm? Explain why this is the case in at most 4 sentences.

We want to determine the motor constant of this actuator. For this we have to study the flux in the magnetic circuit, excluding the field due to the coil.

- (5p) **3b.** Explain clearly why it is not necessary to include the field generated by the coil to determine the force on the coil in this specific situation.

Problem 4: Magnetic circuit

(24 points)

In order to determine the magnetic field in the air gap of the actuator, we will start with a system with only 2 out of 4 magnets, as shown in the upper 2 drawings in Figure 5 (situations A and B).

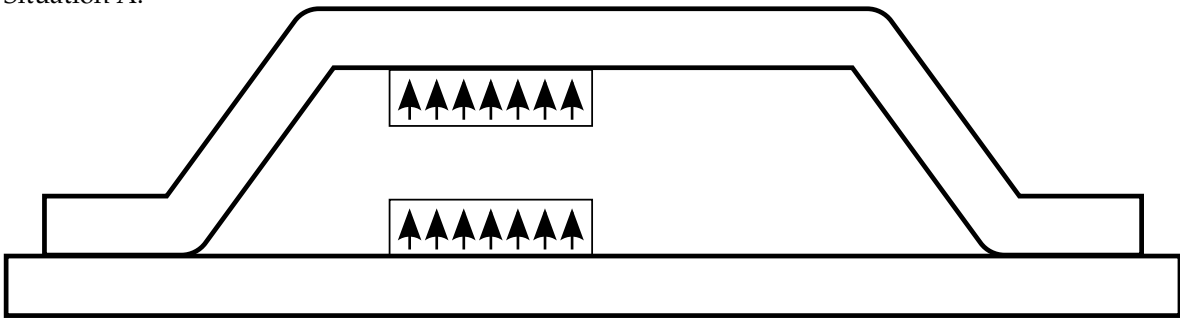
- (6p) **4a.** Draw the magnetic field-lines as you expect them in the top and the middle drawing in Figure 5 (Situations A and B). Pay attention to the flux line density and indicate the flux direction. (To hand in your solutions digitally, please draw on the printed paper, scan your solution and include it in the document you hand in through Blackboard.)

The Hopkinson's law equivalent magnetic circuit is a representation of the magnetic system in the shape of an electrical circuit with as basic elements the magnetic reluctance, \mathcal{R} ; the magnetomotive force, \mathcal{F} ; and the circuit flux, Φ .

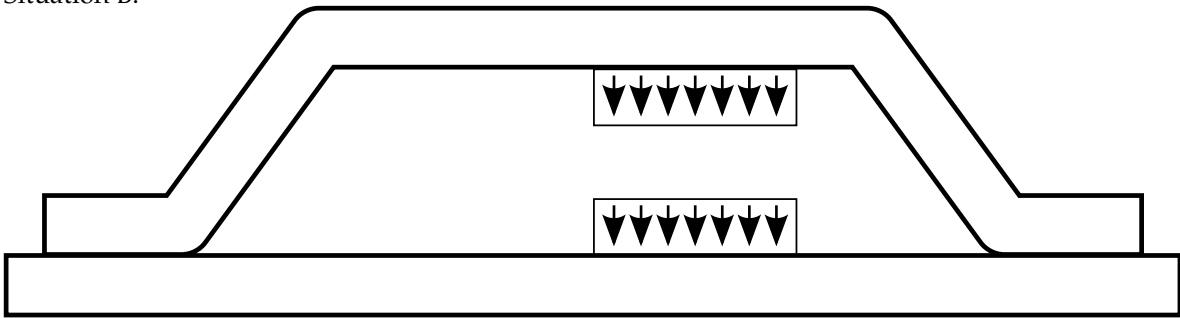
- (7p) **4b.** For Situation A (the top drawing in Figure 5): Make a schematic drawing of the equivalent circuit according to Hopkinson's law using reluctances and magnetomotive force sources. Make sure you include all relevant flux paths and leave out the irrelevant or negligible flux paths. Stray flux paths may be neglected.
- (8p) **4c.** For the same situation as in Question 4b (Situation A): use the Hopkinson's law equivalent circuit to determine the *flux* through the different flux paths and the *flux-density* in the airgap.² Use $\lambda = 0.8$ to take into account the stray flux in the air gap.
- (3p) **4d.** Is the reluctance of the iron parts significant for the fluxes and the flux-density in computed in Question 4c? Give a brief explanation.

²Note that the equivalent reluctance of two parallel reluctances is computed in the same way as the equivalent resistance of two parallel resistances.

Situation A:



Situation B:



Situation C:

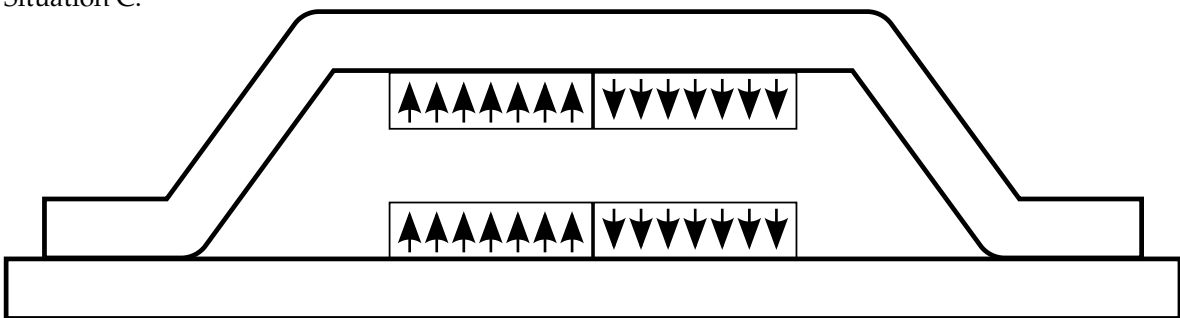


Figure 5: Schematic drawings to draw the magnetic field lines in the partial situations A and B and in the full actuator, situation C..

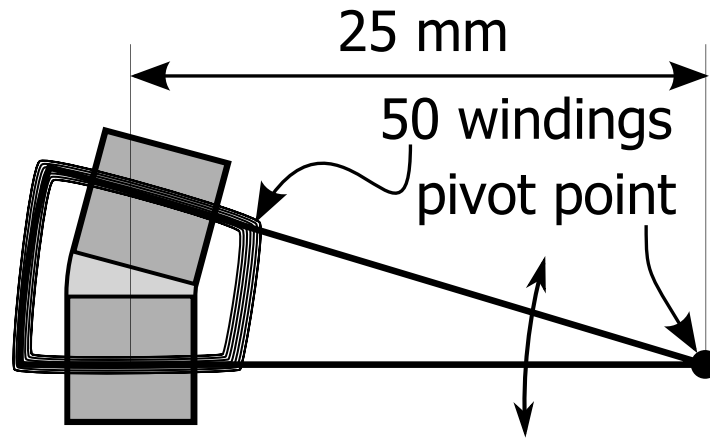


Figure 6: Schematic top view of the HDD arm actuator.

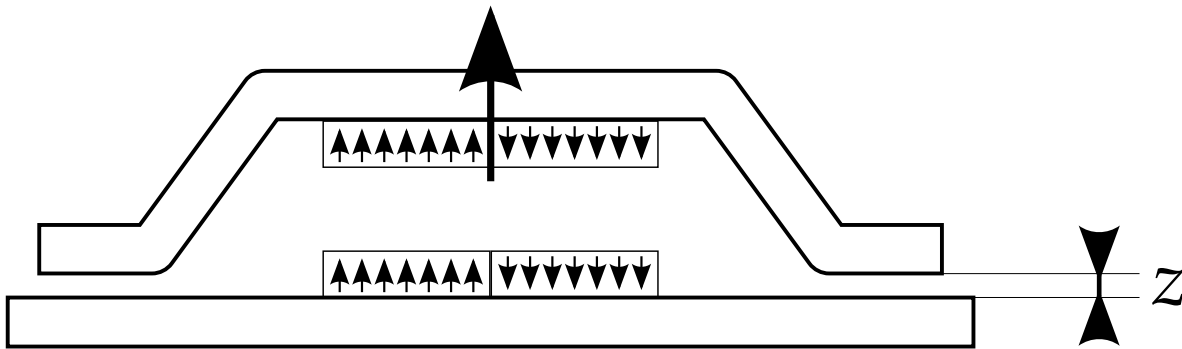


Figure 7: Removing one of the magnet assemblies.

Problem 5: Magnetic superposition

(28 points)

- (6p) **5a.** Superimpose (add) the fields you have found in Question 4a to form the field of the total system. Draw the combined field in the bottom diagram of Figure 5 (Situation C, the system with 4 magnets). Again, pay attention to the flux line density and the flux direction.
- (6p) **5b.** In the flux-pattern you have found in the Question 5a, one path is dominant. Explain briefly why it is a valid assumption that all flux follows this path. Support your reasoning by a flux calculation. Hint: you may use the fluxes computed in Question 4c for this.
- (6p) **5c.** Given that number of windings, $n = 50$, and that the coil is at an effective distance $l_{\text{pivot}} = 25 \text{ mm}$ from the pivot point, as is shown in Figure 6, determine the motor torque constant of the actuator.

When you try to remove the upper 2 magnets and the top of the core from the magnetic system (this motion is indicated by the large arrow in Figure 7) you notice that you need a large force for that. We will compute the 'sticktion force' of this magnet configuration. Note that the coil can be entirely left out for now, as we are interested in the force due to the permanent magnets only.

- (3p) **5d.** Which basic physical/electromagnetic principle generates this force? Explain why this is the case in at most 4 sentences.

We will assume that all flux flows through the dominant flux path discussed in Question 5b; however, the size of the airgap increases with displacement z , as is indicated in Figure 7. Note that there are permanent magnets and there is no current carrying coil in this magnetic circuit. Therefore, the most straightforward method to compute the ‘sticktion force’ is using the spatial derivative of the magnetic energy in the system. In this case the magnetic force is given by:³

$$F_{\text{mag}} = \frac{d}{dx} (-E_{\text{mag}}),$$

where the magnetic energy can be approximated in the Hopkinson’s law parameters:

$$E_{\text{mag}} = \frac{1}{2} \int_V \frac{B^2}{\mu} dV \approx \frac{1}{2} \Phi^2 \mathcal{R} = \frac{1}{2} \frac{\mathcal{F}_m^2}{\mathcal{R}}.$$

- (7p) **5e.** Use the the stored magnetic energy in the system as a function of distance z (indicated in Figure 7) to derive an expression for the force in z -direction as a function of z , and compute the force at distance $z = 0$.

Please indicate the following for each question on your solution:

This question was:

Difficult	↔	Doable
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

I spent:

Hours

³If you follow the entire derivation in Section 5.3.2 of the book, we assume to have only non-zero power storage and mechanical output, so that: $P_{\text{storage}} - P_{\text{mech}} = 0$.