ACKET Adrien
GADEFAIT Paul
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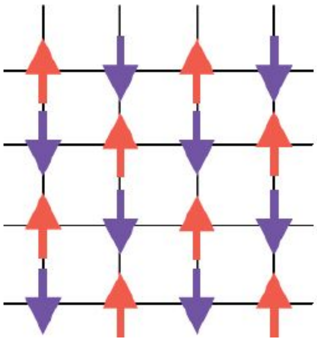
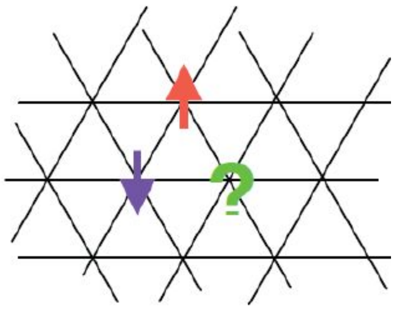
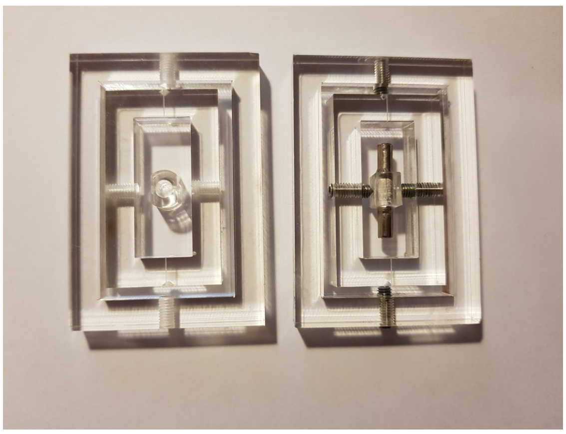
Tutors :
Yacine Amarouchene
Sebastien Burdin

Tutored project report

Macroscopic magnetic frustration







Mesures physiques

université de BORDEAUX

Introduction :

During this project we will work on magnetics interactions. Especially on a phenomenon named magnetic frustration. The goal of the project is to observe a system built with severals magnets. This project is inspired from a study made in december 2012 by Paula Mellado, Andres Concha and L. Mahadeven. These scientists build a lattice made with ferromagnetic rotors. Thanks to this construction they were able to modelling relaxations processes with a macroscopic tool. Lead by our tutors Yacine Amarouchene and Sebastien Burdin, we will build one of these lattice with our own magnetic setup.
The first step of our project is to create some elementary compasses. We use the Fablab's equipment, the laser-cutting machine among others.
We will first study these elementary compass, then we will create the net and equipped it with sensors in order to observe it.

Summary :

Magnetism and frustrations:

Magnetism is a quantum phenomenon due the electrons inside a material.
There are different kinds of magnetic materials, paramagnetic, diamagnetic and ferromagnetic, depending on specifics layout of the electrons.
This microscopic layout have macroscopic effects, 2 magnets can attract and also push away each other. A magnetic north pole will be attracted by a magnetic south pole and 2 north pole repels each other. We could show magnetic interactions by using 2 magnets. If we allow one magnet to rotate and we place the second one near to the first one, we will observe that the rotative magnet will rotate in order to minimize the interactions forces. This is a natural phenomenon, a system will always make the best it can to minimize all the present interactions.
Today the magnetism is used everywhere, for exemple our hard drive store data by using small magnetic fields. The phenomenon need to be perfectly understood in order to improve our technologies. Furthermore we can also use magnetism as macroscopics models to microscopics effects.
It’s easy to guess how the 2 magnet will angle in this kind of system. But if we consider a net made by 3 magnet, the situation becomes harder.
Frustration occurs in a magnetic net when a system is unable to simultaneously minimize all the magnetics interactions due to the design of the net.
If we consider a magnetic net formed by compasses which have 1 mechanical degree of freedom each, we will observe that the system will take one specific design in order to reduce the magnetic interaction. A frustrating magnetic net can take several designs to reduce the magnetic interactions. (Appendix 2)

Objectives:

Concerning the management method, we established a Gantt diagram (Appendix 1). Before every session, we checked the progression of the project, and then we defined the things we had to do during the session.
In this report, we will first explain what is the magnetic frustration, then we will describe the objectives and the work accomplished.

The students of last year, designed a compass model, this model have been worked to reduce the frictions. We will build several compasses based on the previous design.

In a lattice made by a lot of compass, the response speed to a perturbation depends on the frictions, the inertia of each compass and the magnetic interactions. To be accurate in our observations we have to be sure that the frictions and the inertia aren't too strong compared to the magnetic interactions.
Magnetics interactions is a force depending on the distance so we need to find the perfect distance between 2 magnet in order to be in a domain where the magnetic interaction predominate.
The first step of our project is the characterization of the compass we made. We need to find an accurate value of the friction coefficient, the inertia momentum of our compass and the magnetic forces that occurs depending on the distance between 2 magnet. With these value we will determine the ideal distance between 2 compass in our future lattice.
After the characterisation we will build the lattice and we will equipe it with severals hall sensor linked with an arduino card.

The procedure to obtain the data we need is the following : We decide to build a test bed. A compass with 0 mechanical freedom degree will be fixed on a side of the bed test and we will put another compass in front of the first one, the second compass has 1 mechanical freedom degree. The second compass will naturally rotate in order to minimize the magnetic interactions. The second compass will be artificially pull away from its equilibrium position. (Appendix 3) When this artificial force disappear the second compass will tend to go back to its equilibrium position by oscillating.
We will record the variation of the angle took by the rotative magnet. This variation will give us several informations.
The expression of the pseudo-oscillation against time is :

$X(t) = Ce^{-Kt} * cos(\omega_1 t + \phi)$ with : C,φ :Constant relative to the system itself
K : Damping time
ω_1 : The pseudo-pulsation of the system

The record can be done by filming with a high speed camera the test bed with a top view. Or we can also use hall sensors.
We expect kind of record described in appendix 4 for the oscillation of the rotative magnet.
The X-axis represent the time, the Y-axis represent the angle of the rotative magnet.
The informations we will extract will be :

-**The period T** of the oscillation, which depends on the distance between the 2 magnets, it will allow us to determine the interaction force depending on the distance.
-**The logarithmic decrement** will gives us the damping time, it gives us an indication on the frictions that occurs.
-**The acceleration of the magnet**, it'is deduced by derivating it's position. Inertia is the resistance of any physical object to any change in its state of motion. So if we modeling the forces applied on the rotative magnet, and finding the acceleration of it, we will be able to determine the Inertia. The inertia of the magnet itself could have been easily determine with this formula : $I = \frac{ML^2}{12}$ **.** But, as we will see,, the mass of the magnet plastic support isn't negligible.

Concerning the magnetic interaction we know that the force that occurs depends strongly on the distance. After approximately 8 cm the effect of a moving magnet won't affect another magnet. The period of the pseudo-oscillations depends directly on the force exerted.
We will make several measurements of the period and change the distance "d".

Project Program:

1) Work done

The compasses

The compass is composed of three part. The first piece (biggest one) is joined to the second piece (middle one) with two screws in two opposite sides, the second piece can turn in a way. Then, we have a third piece. This one is the smallest one, and it contain the magnet. This piece is joined to the second piece with two other screws (in the other side than the first one). The third piece can turn in the other way. (Appendix 9)

The first manipulation we did was to machine the plastic socket designed by the previous group.
To draw and cut with the laser cutting, we improved our ability in Computer assisted design
The first difficulty encountered concerned the use of the laser cutting machine. The Interface between the computer and the laser software is a bit erratic. We need to make some particular manipulations like changing the color and the size of our vectorial drawing in order to be detected by the software.
The first things to do was to cut the plexiglass using the laser cutting machine. The focalisation of the laser was really important in order to cut precisely and to keep the compass intact.
The biggest problematic we had was the following : thanks to the laser cutting machine, we can create simple plastic pieces. We still need to make the mechanical joints by ourselves..
To make this joints, we need to drill the plastic in a precise point. Then, a screw will join two piece. (Appendix 10)
These threaded holes, will allow a rotation of the magnet according to an axis, and two other holes will allow another rotation on the other axis. The more accurate it will be, the less frictions the system will have. So in order to improve our plastic socket, we will need to find a way to perform very accurate drilling. We first trained to drill it with a drilling machine, but we had to take care not to move when we are drilling, and to drill exactly in the center of the drilling diagram. the results was good but not performing, so we decided to ask for help from the mechanical department of the IUT. A first technician has drill holes necessary for 2 compasses, and then another one has tap holes. When the pieces were ready, we inserted the screw and the magnet, our compasses were done. (Appendix 10)
For the end lattice, we had to create many compasses, and to drill them, but due to time constraints with GMP technicians, we had to drill by ourselves.
To limitate the friction problems due to the contact of the screw on the second piece it joined, we decided to take a needle screw. This kind of screw is ideal because the contact surface of the screw is minimum. Consequently, the friction phenomenon has been reduced. To keep all the compass's elements unified, we also decided to make a footprint in the second piece, and in the piece including the magnet. It shape is conical, as the shape of the end of the screw. In this way, the screw keep a small contact with the second piece and the third one. More, we can choose the degrees of freedom of the rotation. In fact, by tightening the

screw more or less stronger, we can allow the rotation or not. To avoid any magnetic interaction between screws and magnets, we chose a non-magnetic needle screw. (Appendix 11)

Measurements Chain

In order to get a proper characterization, we also realized a test bench. We thought about how we could do the test bench to optimize the measurements. With the cutting laser, we had to face the same difficulties as for the compasses, to cut precisely and not to burn the test bench with a wrong focalisation.
The test bench is made of a wooden plate, there are many slots to put the compasses. The distance between the fixed compass and the rotative one hasn't been taken randomly. We first took some magnetic measurement with our smartphones in order to get an approximation of the value we needed to obtain. We decided to fix a compass, and to place the second compass at two centimeters from the first one (to avoid any contact with the magnet). For the measurements, we moved back the second compass each centimeters and we realized the measurements. (Appendix 12)

The value taken by the rotative magnet can be obtained by using a slow motion camera or a hall sensor. The frequency of the phenomenon we need to observe is included between 10 Hz and more than 100 Hz. The 2012 study from which we got inspired, has been made with a 4 000 fps camera. This kind of camera can cost up to 10 000 $ depending on the resolution wanted. A dedicated slow-mo camera wasn't affordable and there wasn't any of these available in the IUT. A Hall sensor cost less than 10 $, but we need to use it with an arduino card, and to program it, the sample frequency of these kind of sensors reach 100 Hz.
We decided to begin our characterization with a smartphone camera. The sensor contained inside the Samsung Galaxy S8 used can go up to 240 fps. It's a way less than 4000 fps, but with a fine data processing, we will be able to make our characterization.

In addition of our smartphone sensor, we also bought a hall sensor, this sensor will be used to confirm the data we found with the smartphone. It will also be equipped on the final lattice. We build a comparative table to choose the good sensor.

Mesures processing

We used the software "LatisPro" a tracking software developed by Eurosmart in order to exploit our raw videos. This software isn't very powerful, so we had manually plotted the rotative magnet in the picture frame per frame. At the end of the plotting, the software gave us the motion of the magnet following the x and y axis.
With this positions it's easy to deduce an angle value using trigonometric formula.

$$\Theta = Atan(\frac{y}{x})$$

We had an issue concerning the accuracy of the x-motion of the magnet given by LatisPro. This lack of accuracy affected the angle value. For some measurements this lack was too disturbing. We have freed ourselves from the x-values by using another trigonometric formula $\Theta = Asin(\frac{2y}{Length\ of\ the\ magnet})$

Then we used a classic data software like Excel to get and store all our angle value.

At this step, our graph wasn't enough accurate, there was a bias on some of the recordings. As we can see on the appendix 6 : The angle converge to a value different of 0 (The expected converging value). This biased is probably caused by an unwanted moove of the camera during the record or a small rotation of the magnet which was supposed to be locked.

In order to correct this bias we used a software called KaleidaGraph developed by Synergy Software.

The first step was to use an algorithm to smooth the graph, to erase the oscillations fluctuations. This algorithm use the mathematical operation called rolling average. The result of this operations gives us the unwanted bias. So we just needed to subtract the angle values by the bias obtained to get a clear diagram.

Then we need to modeling the graph. We already know the form of the mathematical function behind this graph : $\Theta(t) = Ce^{-Kt} * cos(\omega_1 t + \phi)$

A regular office software isn't strong enough to determine the coefficients we want to obtain. We used again KaleidaGraph. To help the software to converge toward the good values, we help him by entering the formula expected and an approximation of the coefficients. In the exemple gave in the appendix 7, we can see the the unbiased graph modelized by the software. The coefficients wanted are m3 and m4 which correspond to the damping time and the period. Still Kaleidagraph had difficulties to converge on some of the correlations required.

We used an alternative tool, called xlstats, macros working on excel.

2) Results and observations

We've made several measurements in differents slots, the distance between the 2 magnets is indicated. The measurements have been taken for the 2 differents rotation axis.

-The cases 1y, 2y, 3y, 4y are the one taken with the third part of the compass locked (Appendix 5). The moving part of the compass is the secondary. So the compass can rotate following the y axis.

-The cases 1x, 2x, 3x, 4x are the one taken with the secondary part of the compass locked (Appendix 5). The moving part of the compass is the third. So the compass can rotate following the x axis.

Cases	**C1y**	**C2y**	**C3y**	**C4y**	**C1x**	**C2x**	**C3x**	**C4x**
Distance (cm)	2.8	3.8	4.8	5.8	2.8	3.8	4.8	5.8
Damping (s)	0.152	1.498	1.477	1.329	0.029	0.340	0.523	0.633
Pseudo-Period (s)	0.041	0.239	0.397	0.612	0.009	0.06	0.107	0.183
Model quality (%)	92.7	97.7	99.4	97.7	99.4	94.9	99.5	99.0

During the data processing we observed that the mathematical model isn't perfect. There is a variation in the frequency and in the damping coefficient (appendix 8).The modelization can be done for only a fraction of the graph. We know that the model can only work for small oscillating angles. The linearity of the coefficients works only for these small oscillations. Our coefficients have been calculated only for the linear regime.
An example of a poor correlation attempted on the whole recording of one test case is shown on appendix 8. We can see the high discrepancy between the data and the model due to mainly the strong change of periodicity.
In order to get correct correlations, we had to restrict the field of the correlation to 3 to 5 oscillations, excluding the first ones.
Our results shows an interesting point concerning the inertia. In fact if the inertia phenomenon was negligible, the period and the damping of the slot 1 and slot 1x would have been similar. This big difference between 1y, 2y, 3y, 4y and 1x, 2x, 3x, 4x is due to the mass difference between the secondary part and the third part (Appendix 5). The magnet have a higher inertia if it rotates in the y axis than in the x axis. This explains that the pseudo-Period is higher for the 1y cases than for the 1x cases.

The analysis could have been improved if we had a slow-motion camera and a more accurate mathematical model.

3) Remaining work

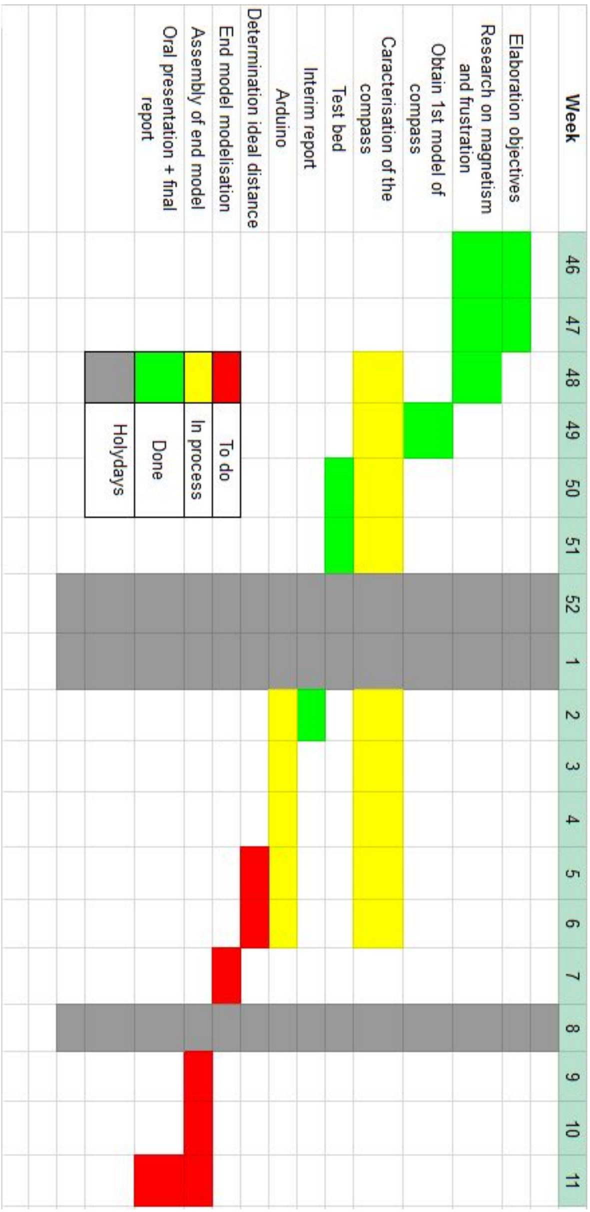
The project isn't completed, there is still some works on the interpretation of the data presented in the tab. The raw data can also be exploited by the next students, these data will be sent as attachments.
We will need to determine the inertia of the 2 rotation axes with another experimental setup.
With this interpretations, the ideal distance between 2 magnets will be determined, and the construction of the lattice will begin.

Conclusion :

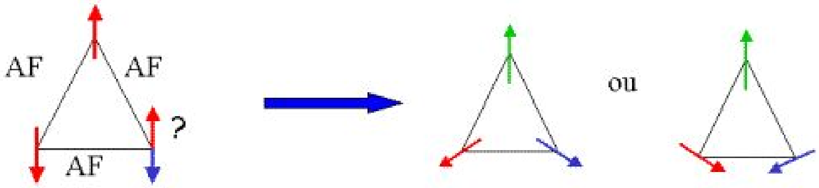
This tutored project has taught us many things. We have learned about mechanics, vibrations, computer assisted design and many differents hardware. We can see an application of what we studied in class, and we could employed our knowledge and skills acquired to a concrete case. Our measurements showed us two differents way to measure something, with different method and exploitation which were more or less longer. It give us an idea of what could be the work world.
For the future student, it’s important to assemble the compass quickly, to start measurements and have time to exploit results obtained. Don’t hesitate to ask for people at school (in MP) or elsewhere. All the data we used will be available on an attachment.

Annex

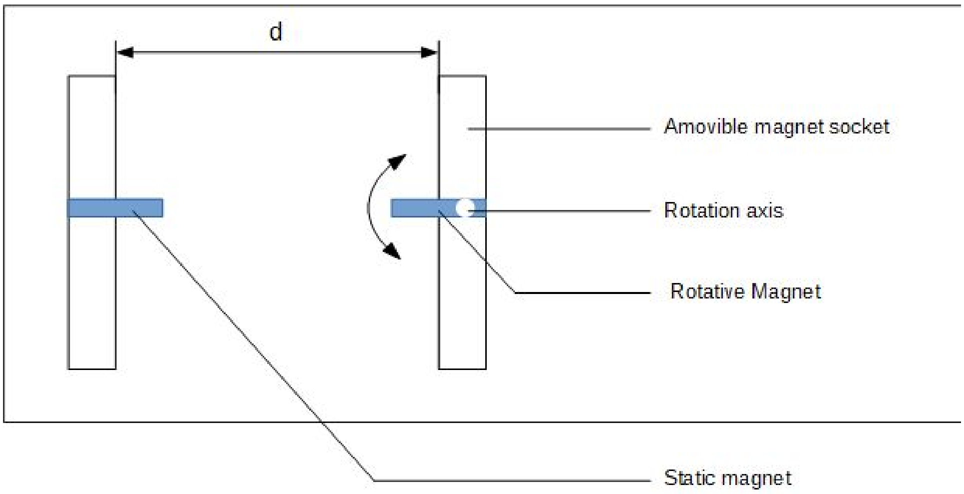
1) Illustration table



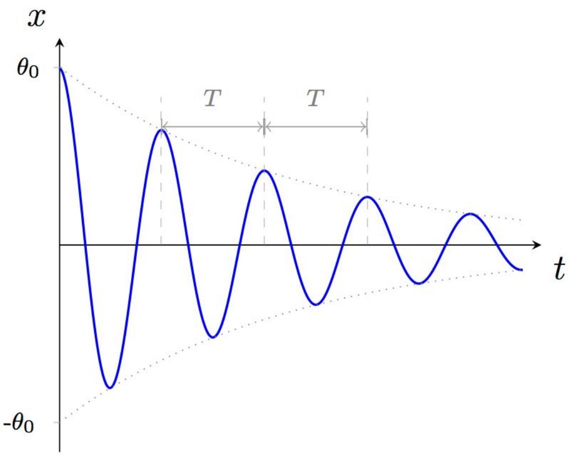
Appendix 1 : Gantt Diagram



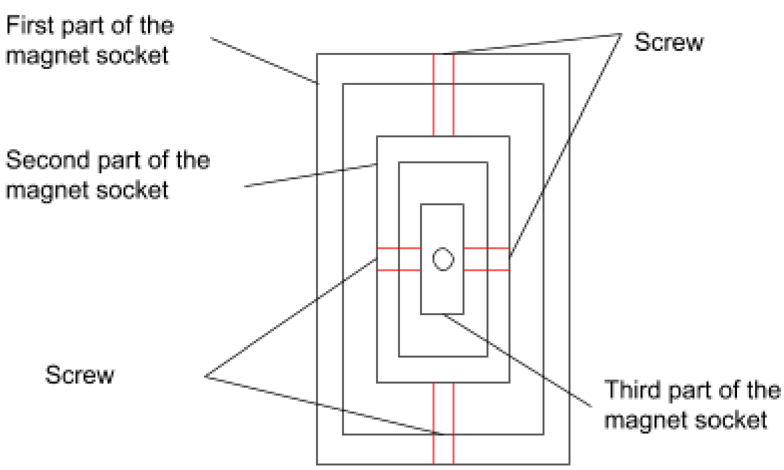
Appendix 2 :<u>Magnetic frustration in a system made by 3 compasses</u>



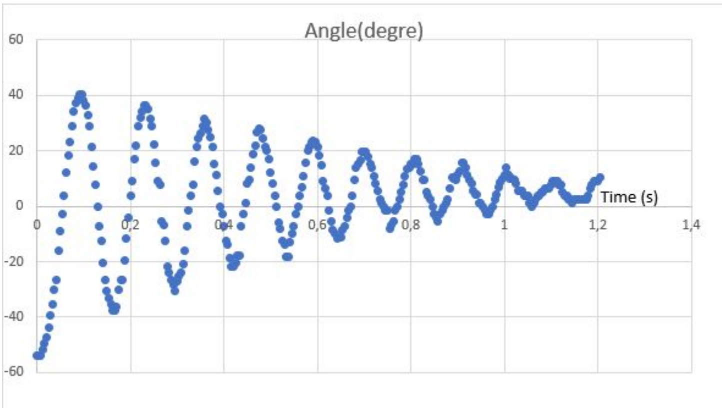
Appendix 3 : <u>Experimental setup</u>



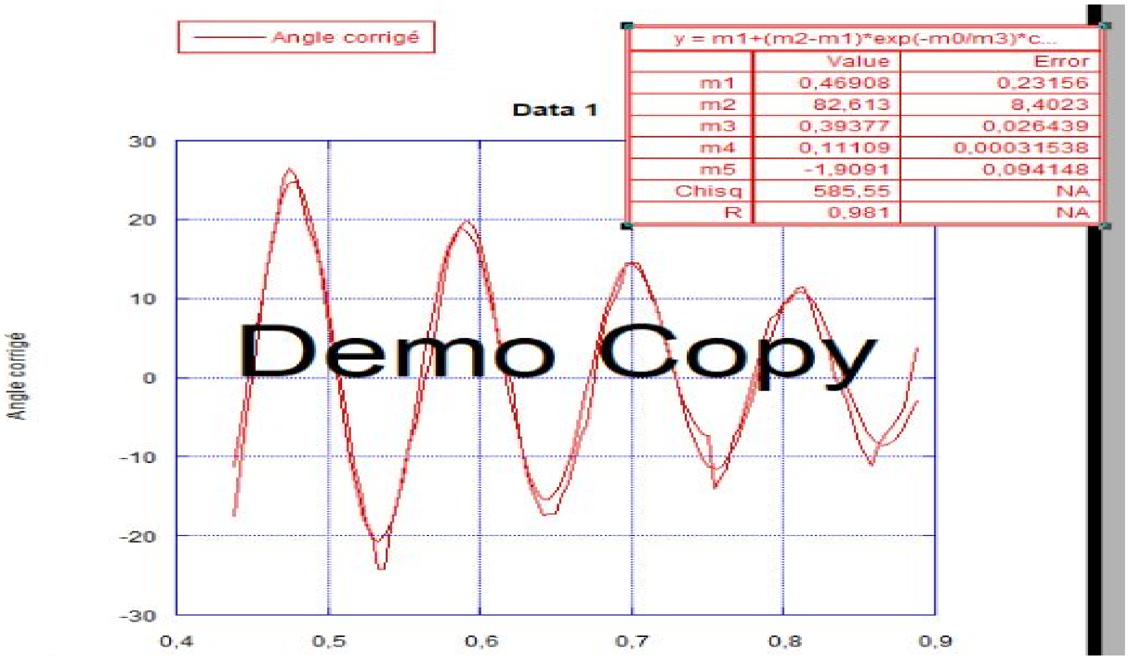
Appendix 4 : <u>Pseudo oscillation of the rotative magnet</u>



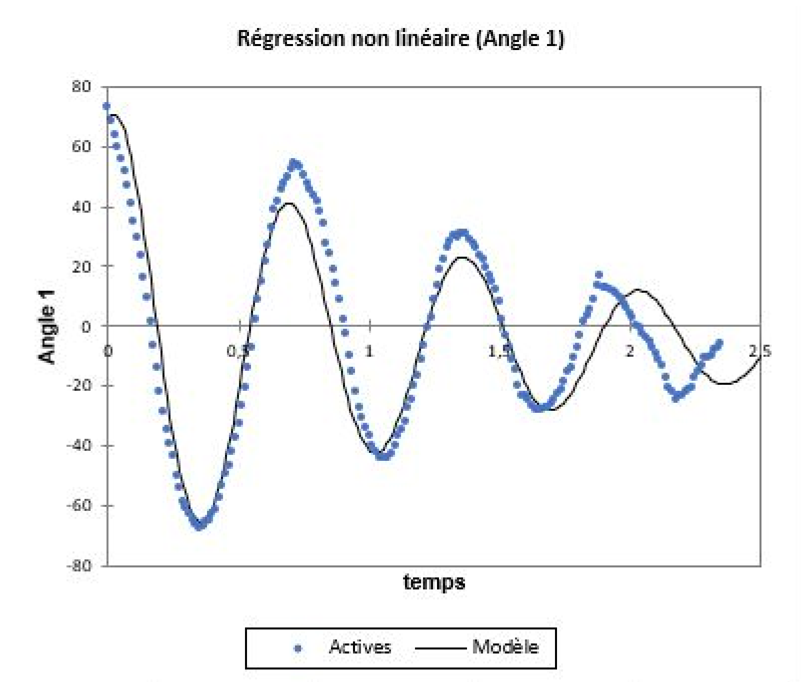
Appendix 5 : <u>Magnetic compass design</u>



Appendix 6 : Biased Angle as a function of time.

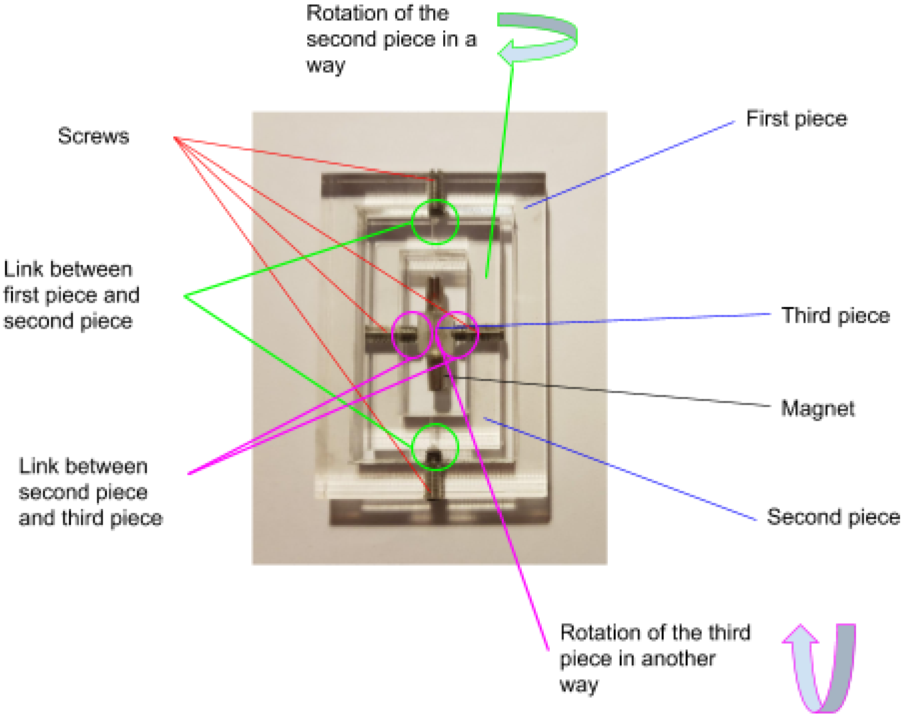


Appendix 7 : Modelization of a graph with Kaleida



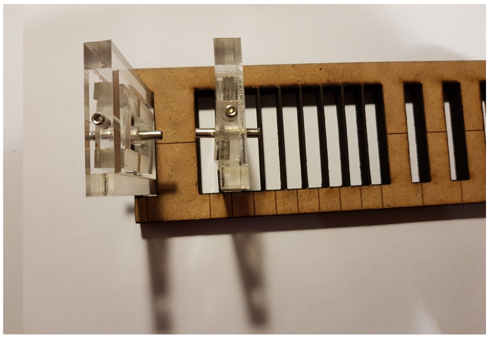
Appendix 8 : Angle graph and its model showing the frequency drift effect

Appendix 9 : Compass functioning



Appendix 10 : Compass without and with the screw

Appendix 11 : Non-magnetic needle screw



Appendix 12 : Test bench

2) Bibliography

We based our protocols and methods on the work of Paula Mellado, Andres Concha, L.Mahadevean. Macroscopic Magnetic Frustration (21 december 2012)