Macrospin Dynamics Modeling

Magnetization Precession in Spin Valves and Magnetic Tunnel Junctions

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Introduction

With computational electronics rapidly approaching the thermal and quantum limits of what's possible, and fabrication limits of technology being stretched, more and more research is being devoted to exploring nanoscale level logic devices. Magnetic spin valves and magnetic tunnel junctions have potential for replacing their electrical equivalents, with the potential for applications in MRAM as well as hard drive disk read heads, as well as future applications in magnetic logic circuits, and low-profile non-volatile information storage. The structure relies on two magnetic layers, one "hard" ferromagnet (fixed layer), and one "soft" ferromagnet (free layer), the magnetization vector of the latter determines the state of the valve, which can either be parallel or antiparallel, affecting the resistance of the valve, which is the main tool of interest for these devices. However, when considering real-world scenarios, we have to account for how the free layer magnetization resolves to one of these two states from a thermal (random) state, and if there are conditions under which neither of the two poles is reached given an arbitrary timescale. The goal of this project is to find states in which the magnetization precesses but does not resolve to one of the two possible directions, resulting in a limiting cycle. Once these limiting cycles are reached, the next goal will be to parametrize the conditions under which such a cycle occurs, and hopefully replicate it in a lab setting.

Spin Valves and Spin Transfer Torque

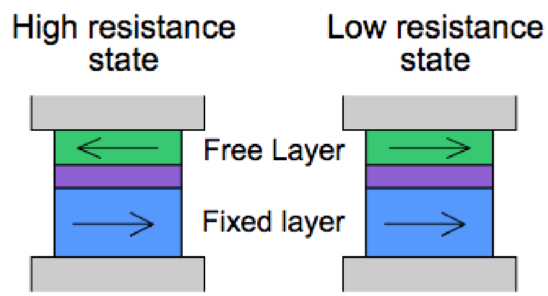

Figure 1: Simple Diagram of a Spin Valve

A spin valve is a combination of two ferromagnets with a thin insulating layer between the two of them. The key interaction between them is a phenomenon known as Spin-Trasnfer Torque, in which passing a current of electrons through the fixed layer results in a current of spin-polarized electrons. These electrons tunnel through the thin insulator into the new free layer. The angular momentum of this spin polarized current is transferred to the free layer, resulting in a torque on the magnetization of the free layer. Varying the angle of the fixed layer's magnetization, as well as varying the intensity of the torque applied (by current) are all adjustable parameters to change the torque vector applied, and varying these parameters was the main method of locating limiting cycles.

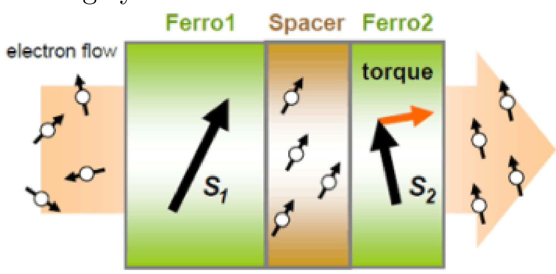

Figure 2: Spin Torque

Spin Dynamics

The precession of a magnetization in a material is governed by the Landau-Lifshitz-Gilbert equation, defined as:

$$\frac{dM}{dt} = -\gamma(M \times H_{eff} + \alpha \frac{M}{M_s} \times (M \times H_{eff})) \tag{1}$$

Where M is the magnetization vector, α is some damping constant, M_s is the magnitude of the magnetization, and H_{eff} is the effective field, as defined by the demagnetization field, and an external field. The demagnetization field of a thin solid can be written in the form:

$$H_{demag} = H_0(D\hat{z} - \hat{x}) \tag{2}$$

Where D, is some constant determined by the material. In this project, it was suggested that I use 10, which correlates with the Silicate currently used in Kent lab applications.

This equation can be split into two components, the precession component, which points perpendicularly to the magnetization direction (a torque). There's also a damping component, pushing it back towards the poles of the system.

The other relevant torque component acting on the system is the aforementioned Spin Transfer Torque, which acts in the following way:

$$\frac{dM}{dt} = \beta M \times (M \times M_P) \tag{3}$$

Where the M_P is the magnetization of the hard layer, and *beta* is a parameter determined by the current passing through the plates. When considering for all this, we can write an equation of motion simply as the sum of the Landau-Lifshitz-Gilbert equation, and the spin transfer torque term, and solve it given an initial magnetization direction.

The resulting equation is a first order differential equation which we can easily solve using an adaptive RK4 method, optimizing for better speed.

Plotting Methods

The previous method of solving this problem for a random distribution was a bitmap over the surface of a unit sphere, solving the final position given that initial condition, and coding it as such. This method, while pretty, is extremely computationally expensive. My method was picking initial points, and plotting the traces of the path of the magnetization, which is good because the problem is deterministic, so recalculating points passed over in a previous measurement will no longer be redundant, saving on computational time. This is, however, inefficient at higher densities, as we see in my initial results.

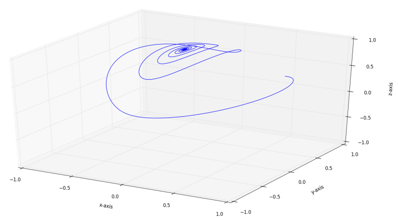

Figure 3: An early test of the LLG equation for a single path

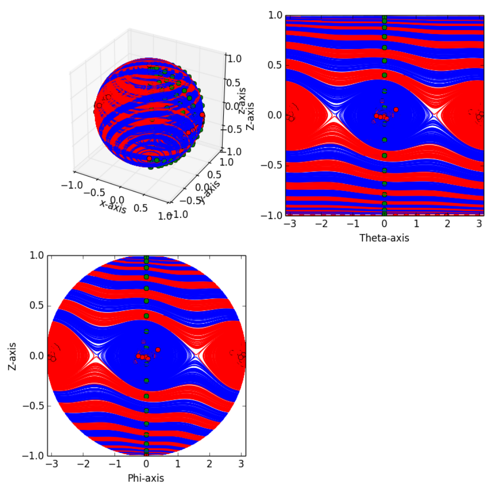

Figure 4: A dense plot using a ring of start points

The solution to this was to utilize critical points, determined by an energy minimum, which take the form as a saddle point. By picking 4 initial conditions about these critical points, we solve for the boundaries of all initial states, which saves massively on computational time.

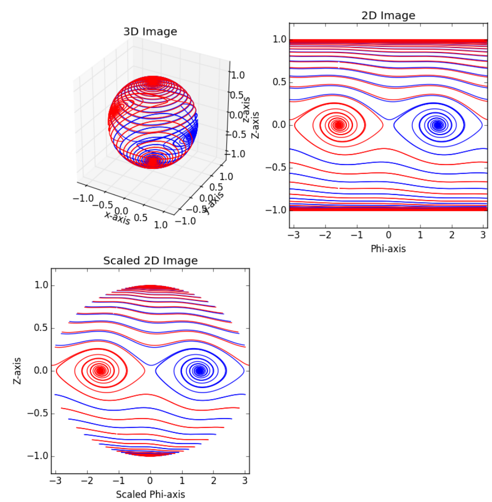

Figure 5: Utilizing a critical point to trace region boundaries

The logical next step is to automate this plotting method. However, locating the energy minimum turns out to be a relatively nontrivial task[1], and I didn't have time to complete this between graduate school applications[2], but using a 3D Newton-Raphson scheme to solve the condition $\frac{dM}{dt} = 0$, it should be possible. My attempt did not work for the simple case (no external field, no spin transfer torque), so I did not implement it in the final solution, opting instead for random guessing. which while not efficient, still produce the desired results.

Limiting Cycles

The limiting cycle is a stable periodic motion in which the magnetization precesses infinitely, and no pole is reached. This behavior is not desirable in a binary switch, and

[1] When I suggested this to my research advisor, he laughed. For awhile.

[2] Which were due on the same day as the presentation for this project.

as such, understanding this phenomenon is incredibly important for the future of this technology.

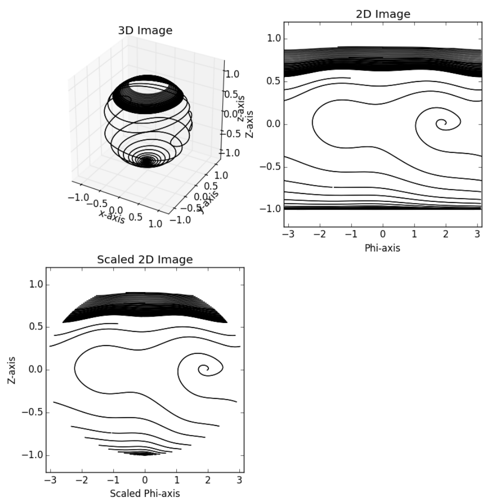

Figure 6: The paths on the top spin down to a repeated circle, indicating a limiting cycle

To identify these, my initial idea was to utilize Poincaré Mapping, but this turned out much harder to implement than a temporary solution, which is measuring the θ variations at some fixed ϕ, essentially seeing if the paths stay at the same value θ as they precess. If they converged, and stayed withing some accuracy parameter, they were considered to be limiting cycles. This can be observed very easily in a graph, and given a tolerence parameter ϵ, I was able to locate them automatically. By varying the aforementioned parameters, and locating the limiting cycles, we now would have a stronger understanding of when these limiting cycles are present.

Results

My test range was a plate magnetization from 0 to 90 degrees tilt of the fixed layer, with the strength being varied from 0 to equal to the precession term of the LLG equation. This data has been saved and included in the git repository. From here, I located limiting cycles in some group, with a clear trend, but for a clearer understanding of the system, I likely have to take data at a higher resolution. This data took a little bit more than a day to run, and I ran into memory limitation issues, meaning a large portion of my data was lost. Still, the data shows a pretty clear trend towards limiting cycle identification. Furthermore, due to the nature of this project, it is difficult to measure the accuracy of my results, as research into this system is currently being done primarily experimentally, and such data was not made available to me.

Improvements

The first step to improving this project is using Poincaré methods to improve the detection of limiting cycles, as it will speed of the identification process. Similarly, automating the solution to the energy equation will allow for the critical points to be more easily located, improving the overall quality of the data points. From a larger scale, I could incorporate parallelization or GPU utilization to run the code even more efficiently.

References

[1] Chaves, Wolf, Pinna, Kent, Micromagnetic study of spin transfer switching with a spin polarization tilted out of the free layer plane, New York, Journal of Applied Physics 117, 2/4/2015

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[4] Newman, M. E. (2013). Computational physics. Place of publication not identified: Createspace.