A mechanical analog of nuclear magnetic resonance.

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NMR is often a complete black box to students. This makes it difficult for them to understand what is physically going on in the system. For example, the students may ask: "what is the resonance in NMR?" This is even more problematic when one uses a pulsed NMR device.

This type of problem exacerbated in the transition from the introductory to intermediate laboratories. In intermediate laboratories the students are dealing with much more complex phenomena. They often use "black box" instrumentation in which they have no idea how it works or even what it is measuring. All of this inhibits the students learning physics.

Our general approach in the Modern Physics laboratory (our first intermediate laboratory after introductory physics) is one that involves tracks of investigation and a lot of scaffolding. A track is simply a sequence of investigations that are conceptually related. A student will stay within a particular track for the entire semester. In the case of NMR, the student will concentrate the entire semester on resonance effects. In particular, a track will generally start with a mechanical analog of what they are investigating. This allows the students to work with something they are more comfortable with and develop some understanding of the basic principles.

For the NMR track, students will start with a driven cart (or two) on a spring. They can vary the driving frequency and observe when resonance occurs. This introduces them to the idea of resonance. They then proceed to working with an RLC circuit and seeing electronic resonance. This introduces them to oscilloscopes and another way of looking at resonance. Originally, we then jumped to using our pulsed NMR. This proved to be too big a jump and the students were often confounded by the change in instrumentation. For this reason we developed the mechanical analog of NMR you see today.

The apparatus is assembled of PVC, an air-bearing, a magnetic sphere, two sheet magnets, and a pair of Helmholtz coils. The magnetic sphere spins in the air-bearing due to turbine torque and acts as an ensemble of protons in the NMR system. The Helmholtz coils allow us to supply an AC magnetic field to perturb the sphere and search for resonance. The sheet magnets are on a slide. By moving them closer or further from the air bearing, we adjust the magnetic field at the sphere. The field at the air bearing is relatively uniform.

Apparatus

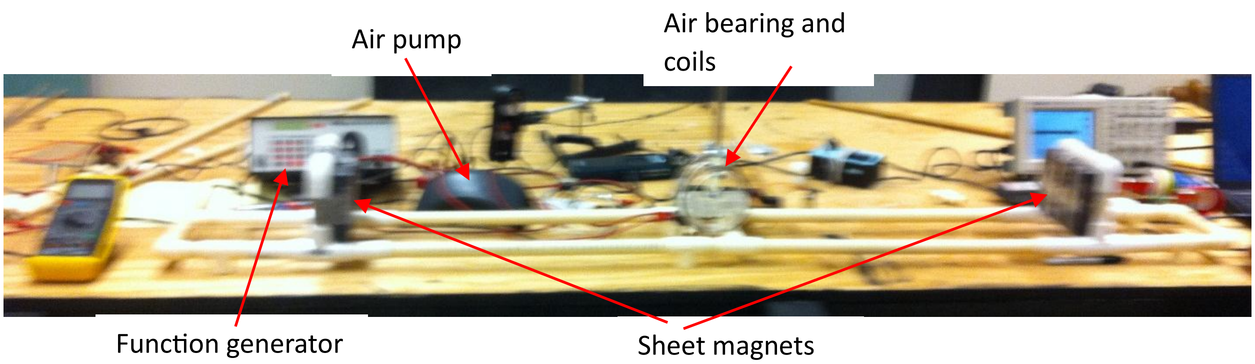
The apparatus itself is quite simple. It consists of an air-bearing which is made by simply using a 1" bull nose (rounded) milling end on a piece of plastic (acrylic in this case). A small hole (<1/16") is drilled through the center of the bearing. On the opposite side we simply attach a pipe to tube fitting (this is similar to that in the article in AJP **77**, pp764). We use an aquarium air pump (using both outputs). In this case, it is necessary to have a small volume under the bearing because the air pump pulses.

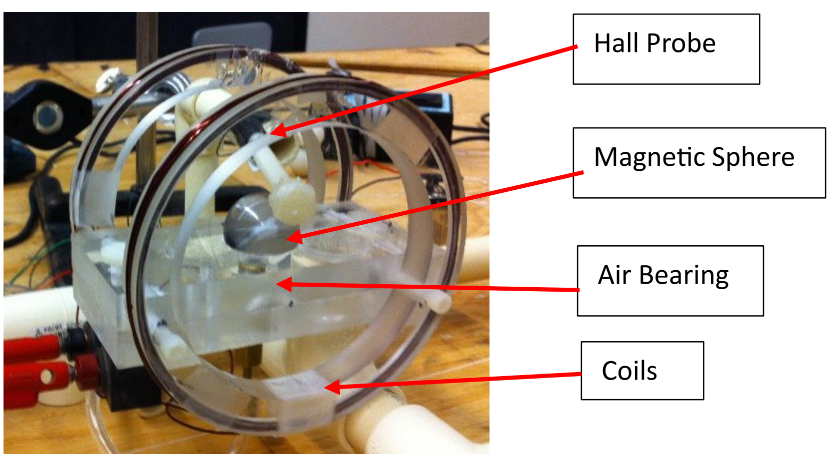
The magnetic spheres are made by taking a 1” acrylic sphere and boring it out to allow the placement of Nd magnet rods inside. One must be careful not to have the rods either in too far (leaving a hole on the surface) or out too far.

We originally used Helmholtz coils to produce the guide magnetic field. However, we found the use of variable position permanent sheet magnets to be more convenient. The sheet magnets are simply mounted on PVC tubes.

We also made a small pair of Helmholtz coils to be our oscillating driving field. We are simply using a double pole double through relay configured as a cross-over switch to flip the current direction in these coils. A function generator provides the signal to the relay. This will soon be replaced by a dedicated microcontroller circuit. This system supplies a square wave oscillating magnetic field. However, we will also be replacing this with a sinusoid.

The sensor is a Hall probe so we can tell the orientation of the magnetic field of the sphere. We also provide a stripe on the ball so that we can optically measure its angular speed.



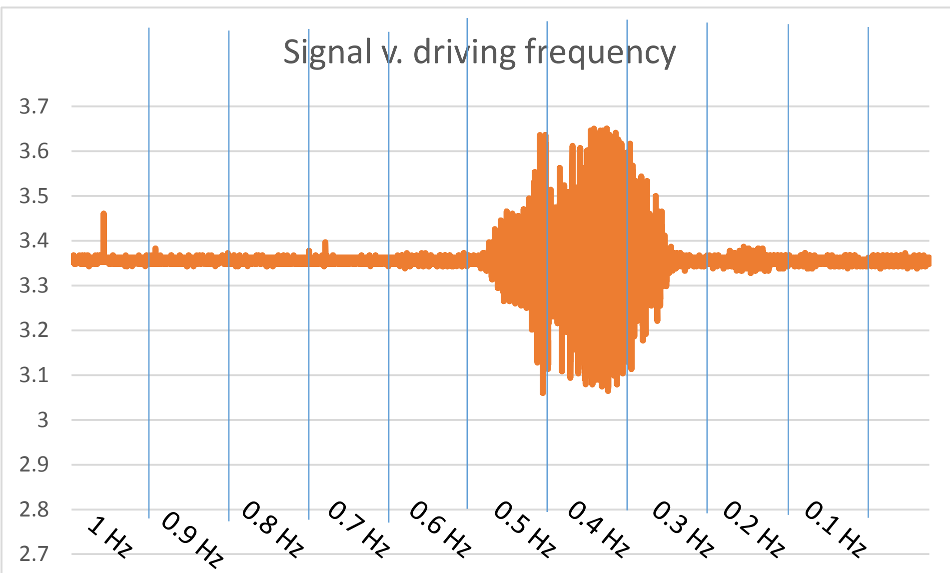


Investigations

What is really important is that the apparatus help the students develop a model of what goes on in NMR; what is meant by resonance in this context. To that end, we start with having them figure out the basic relation the precession frequency of a magnetic moment with angular momentum in an external magnetic field (our spinning magnetic sphere). After this, it is time to start playing to figure out what measurements to make.

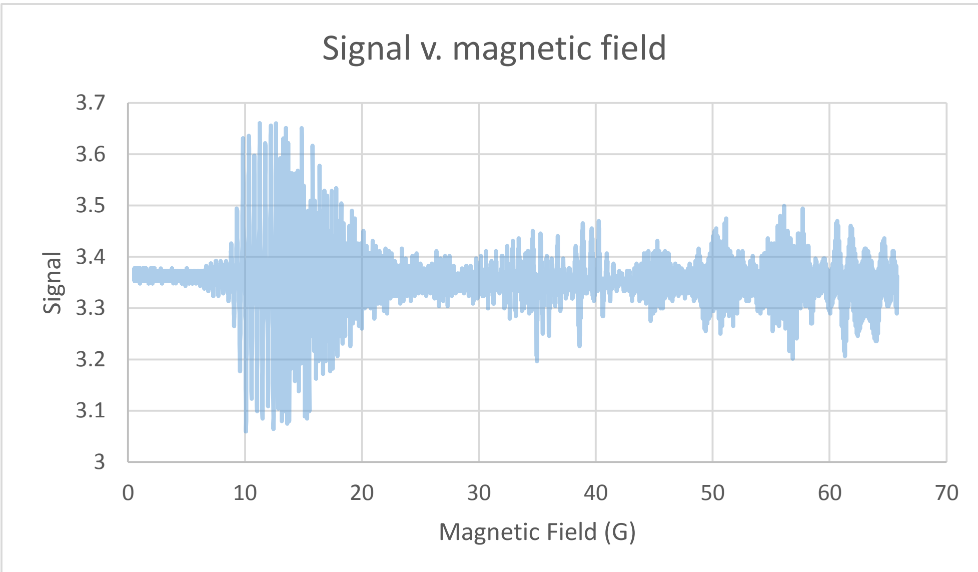
Experiment 1 Swept Driving Frequency

For a given external magnetic field (the two sheet magnets are fixed at some location) we can vary the driving frequency to the small Helmholtz coils. As we increase the frequency we find that the size of the precession becomes larger – i.e. we have found resonance. This is the most similar to what they did mechanically with a system on a spring. For example, they can determine the magnetic moment of their sphere doing this experiment.



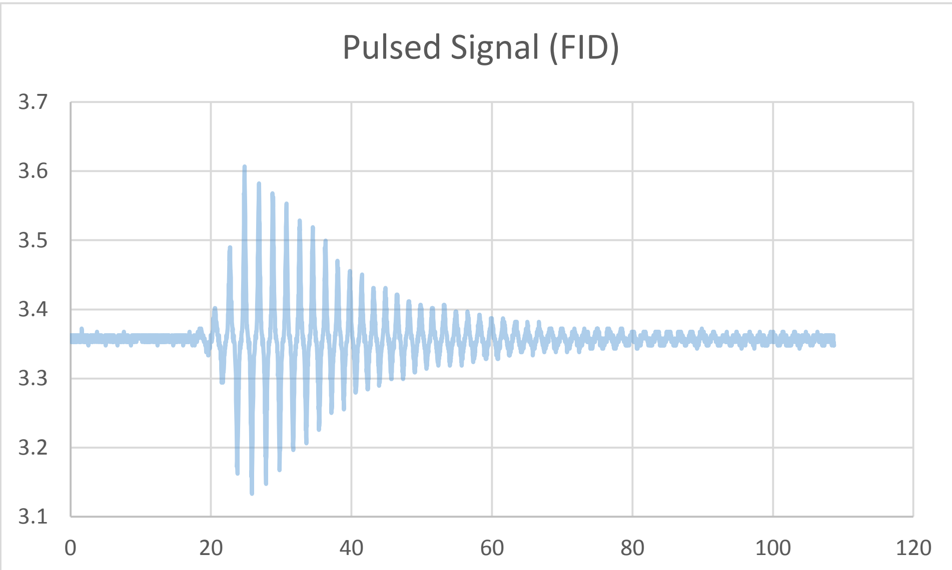
Experiment 2 Swept Magnetic Field

In this investigation, we change the magnetic field the spinning sphere experiences by moving the pair of sheet magnets (this is calibrated by the students) while maintaining a fixed driving frequency. This too allows us to find a resonance frequency for the system and to calculate the magnetic moment of the sphere.



Experiment 3 Pulsed

We can provide a short current pulse to the driving coils and examine the magnetic signal produced by the precessing sphere using FFT. This method is perhaps the most confusing to the students because they can become confused by what is going on and it typically requires discussion and perhaps even reversion to the system on a spring. Regardless, the students explore pulse duration and pulse sequences while looking at the precession signal.



Conclusion

We have found this approach to be helpful in getting students to actually understand what they are doing. We have them explore the impact of structure around the sphere (metal objects, other magnets, etc). We are presently working on adding a second spinning ball with a different magnetic moment so that we can get multiple resonances, looking at asymmetric fields and examining a model of MRI.