

# Exploration of Quartz Tuning Forks as Potential Magnetometers for Nanomagnets

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August 1, 2012

## **Abstract**

A change in the resonance frequency,  $f_0 \approx 32$  kHz, of quartz tuning forks is expected when nanosized magnetic particles or films are applied to a fork that is then exposed to a variable magnetic field. This work explores the feasibility of using these forks, once removed from their protective canisters, as potentially inexpensive magnetometers operating at room temperature in fields up to 2 T by analyzing the responses of loaded forks in such a field. However, the forks are also dependent on subtle variations of the ambient temperature, and the magnetic leads may present a background signal that must be subtracted. Preliminary results are encouraging, but better understanding of the noise sources must be made for these forks to be used as envisioned.

## I. Introduction

When a quartz crystal tuning fork is loaded with a sample of magnetic nanoparticles and placed in a magnetic field, its resonance frequency is proportional to its overall magnetic moment, offering a means of taking magnetic data of materials.<sup>1</sup> Comparatively inexpensive and free of the burdens of helium-cooling, these sensitive and ubiquitous forks present several advantages over SQUID (Superconducting QUantum Interference Device) magnetometers,<sup>4</sup> and with a burgeoning worldwide interest in nanotechnology, low-cost methods in analysis of magnetic materials are crucial.

Constructed from quartz, a fork oscillates mechanically in response to a given voltage, resonating at a particular frequency (32.768 kHz at 25°C and unexposed to air).<sup>2</sup> Structurally, each fork consists of two tines connected to a base, a single piece of quartz, together sealed in a can under near-vacuum conditions to prevent dampening from the air.<sup>2</sup> With sufficiently small amplitudes, the oscillation of the fork can be described by a one-dimensional model, where the tips of the tines approach and recede out of phase with each other, described by

$$m \frac{d^2x}{dt^2} + \beta \frac{dx}{dt} + kx = F_0 \cos(\omega t + \delta), \quad (1)$$

where  $m$  is the mass of one tine,  $x$  is the displacement of the tine,  $\beta$  is the dampening constant,  $k$  is the spring constant of the tine,  $F_0$  is the amplitude of the AC driving signal,  $\omega$  is the driving frequency, and  $\delta$  is the phase difference.<sup>5</sup> From this equation,  $x$  can be solved and expressed as  $x(t) = x_a \sin(\omega t) + x_d \cos(\omega t)$ , where  $a$  and  $d$  correspond to the absorption and dispersion components of the oscillation, respectively. Additionally, the

resonance frequency can be solved and expressed as  $\omega_0 = \sqrt{k/m}$ , and the “quality factor” ( $Q$ ), which can be thought of as a measure of the sharpness of the resonance peak, can be expressed as the ratio of the energy stored in the fork to energy lost during each oscillation period,<sup>5</sup> or equivalently, the ratio of the resonance frequency to the width of the absorption curve at half of its maximum value (“full-width-half-maximum,” or simply FWHM),  $Q = \omega_0/\Delta\omega$ .<sup>3</sup> Inside its protective can, the quartz tuning forks being tested typically possess  $Q$ -values on the order of  $10^5$ , but when removed from the can and exposed to air (increasing dampening), the  $Q$ -value typically falls to roughly  $10^3$ .<sup>7</sup>

Mechanical oscillation is only half of the story. As a piezoelectric structure, the fork also creates an output voltage and can be modeled as an RLC circuit:

$$L \frac{d^2 I}{dt^2} + R \frac{dI}{dt} + \frac{1}{C} = \frac{dV}{dt}, \quad (2)$$

where  $L$  is inductance,  $R$  is resistance,  $C$  is capacitance,  $I$  is current, and  $V$  is the driving voltage.<sup>3</sup> Solving this equation yields similar results to solving the mechanical equation, particularly,

$$I(t) = I_a \sin(\omega t) + I_d \cos(\omega t), \quad (3)$$

where again  $a$  and  $d$  correspond to absorption and dispersion. The absorption component,

$$I_a = \frac{I_0 (\Delta\omega)^2 \omega^2}{(\Delta\omega)^2 \omega^2 + (\omega^2 - \omega_0^2)^2}, \quad (4)$$

yields a theoretical prediction for the fork resonance curve,  $I_0$  corresponding to the resonance current, and  $\Delta\omega$ , the FWHM value.<sup>3</sup>

However, the reliability of quartz tuning forks as magnetometers has yet to be fully verified. Excessive driving voltages, temperature fluctuations, and background response from the fork are all issues that can negatively affect the accuracy of magnetic measurements. (In fact, the thermal sensitivity of quartz forks has led to their use as thermometers.<sup>5</sup>) Here, we show that these effects can, at least to some degree, be quantified and subtracted during the analysis of the data, yielding somewhat promising results for quartz forks as potential magnetometers, the goal being to generate a  $B_c$ , the coercive field, of powder from a ceramic speaker magnet (figure 1).

## II. Methods

An Agilent 33220A function generator supplied an AC signal to the tuning fork, by way of a special platform designed to be lowered into bore of an Oxford nine-Tesla magnet set to two Tesla (using data for the strength of the field as a function of depth gathered by Mathew Calkins). The signal from the fork was analyzed by measuring the voltage across a 1 k $\Omega$  resistor in the feedback loop of a LF411 op amp with a SR530 lock-in amplifier (the op amp also providing a virtual ground for the signal generator). The lock-in then read the X and Y channels of the signal (with a phase difference set to 0° to eliminate mixing of the two channels), and the Y channel was recorded to test for resonance (figures 2 and 3). During experimentation, the signal generator swept through a range of frequencies that contained the resonance frequency of the fork, in increments controlled by LabView, and to test the forks in various magnetic fields, the platform holding the fork was lowered via a stepper motor into the magnet, running a full frequency sweep every centimeter both descending and ascending.

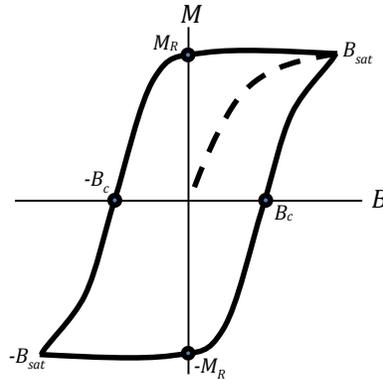


Figure 1: The standard hysteresis loop for magnetic materials, plotted as magnetization ( $M$ ) versus magnetic field ( $B$ ), where  $B_{sat}$  is the saturation field,  $M_R$  is the remnant magnetization, and  $B_c$  is the coercive field.

Once compiled in LabView, the voltage outputs of the forks were exported to Origin and smoothed using the Savitzky-Golay method (i.e., performing a local polynomial regression at each point) in a script, and the derivative of the resulting curve was found. Where this curve crossed zero was taken to be the resonance frequency of the fork (figure 4). To measure  $Q$ , the same smoothed curves were fitted with a Lorentz curve, whose FWHM (Full-Width-Half-Maximum) values were then used to compute the corresponding quality factors. The Lorentz fit was not used to measure the resonance frequency because it proved inconsistent in matching the data curves.

Additionally, care had to be taken not to overdrive the forks with an excessive amplitude of AC signal, an effect manifested in a nonlinear  $Q$  response. Thus, the resonance curves of a closed fork were measured from 10 mV to 1 V (Figure 5).

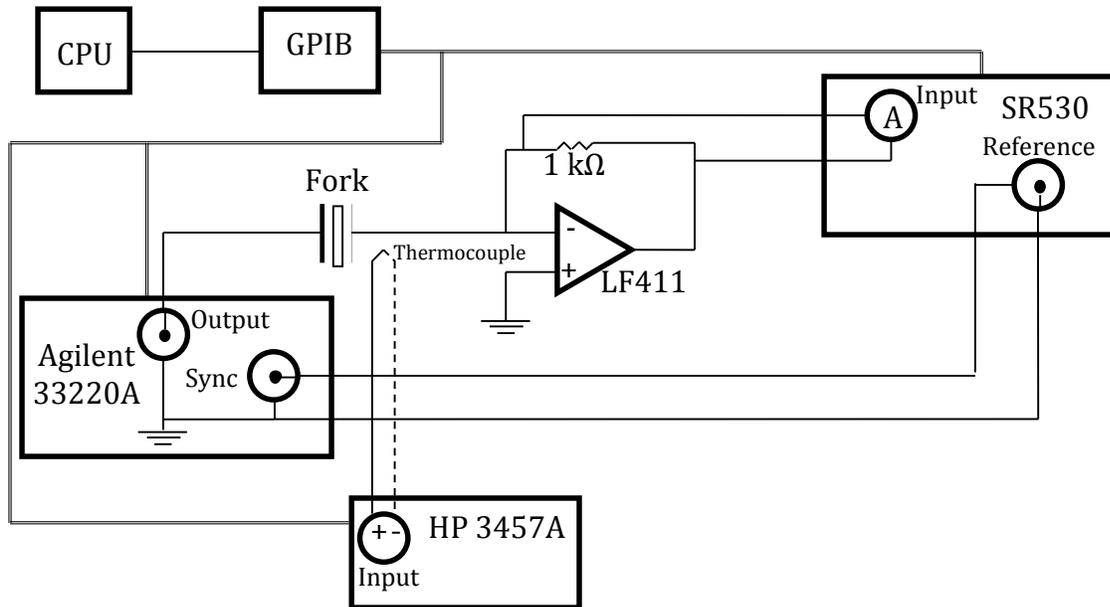


Figure 2: The circuit diagram. The Agilent 33220A signal generator sends a sinusoidal AC signal to the fork, and the response is measured via the voltage across the 1 kΩ resistor in the feedback loop of a LF411 op amp by the SR530 lock-in amplifier. Temperature measurements are taken with the HP 3457A multimeter via measuring the voltage in a thermocouple.

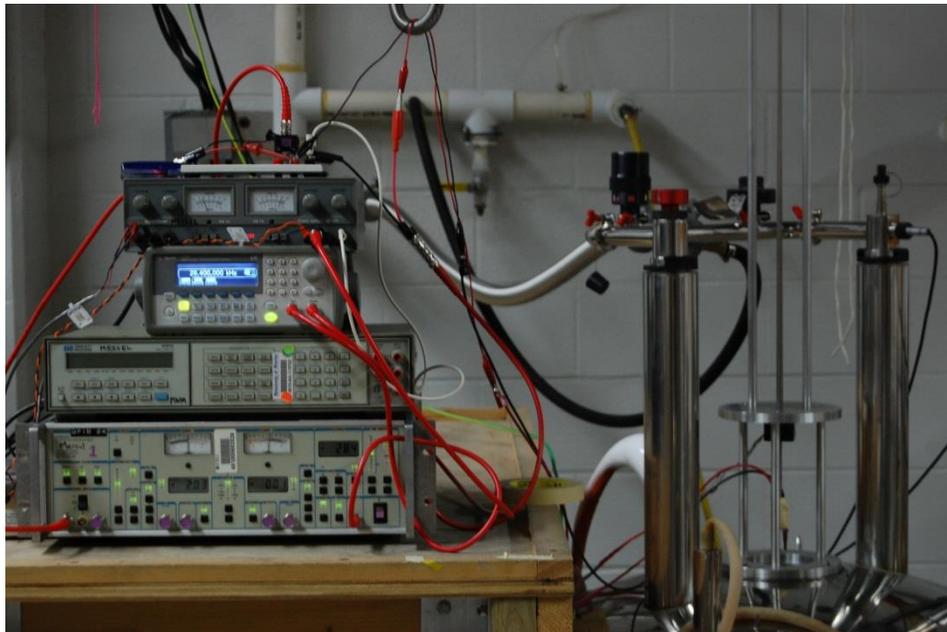


Figure 3: The setup during data collection. On the right, from top to bottom: the op amp, power supply, signal generator, multimeter, and lock-in amplifier. On the left, wires run from the setup to the screw of the stepper motor above the magnet.

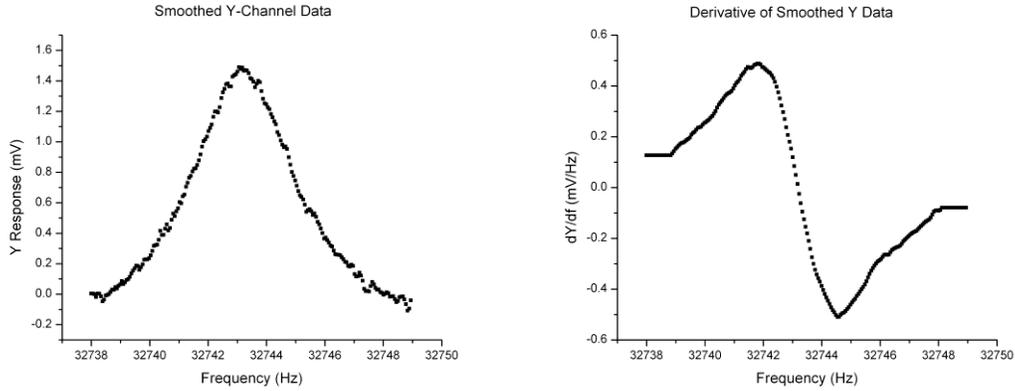


Figure 4: Plot of the smoothed Y channel from open fork four (OF4) and its derivative. The resonance frequency was taken to be the point at which the derivative crossed zero.

In an effort to maximize the precision of the results of sweeping forks through the magnet, temperature was also considered. The resonance frequencies of quartz tuning forks are highly sensitive to temperature, approximately given by

$$f = f_0[1 - B(T - T_0)^2], \quad (5)$$

where  $f_0$  is the resonance frequency at 25 degrees Celsius ( $T_0$ ),  $T$  is the air temperature, and  $B$  is the parabolic coefficient of the fork ( $0.04 \times 10^{-6} \text{ } ^\circ\text{C}^{-2}$ ), as reported by the manufacturer.<sup>6</sup> The temperature was measured by attaching the end of a thermocouple to the fork platform and converting its voltage output on a HP 3457A digital multimeter. The change in resonance frequency caused by temperature,

$$\Delta f = -f_0 B (T - T_0)^2, \quad (6)$$

was then subtracted to correct the data.

Once measurements had been taken with closed forks, their protective canisters had to be removed, a task done by gently grinding the metal attaching the canister to the forks'

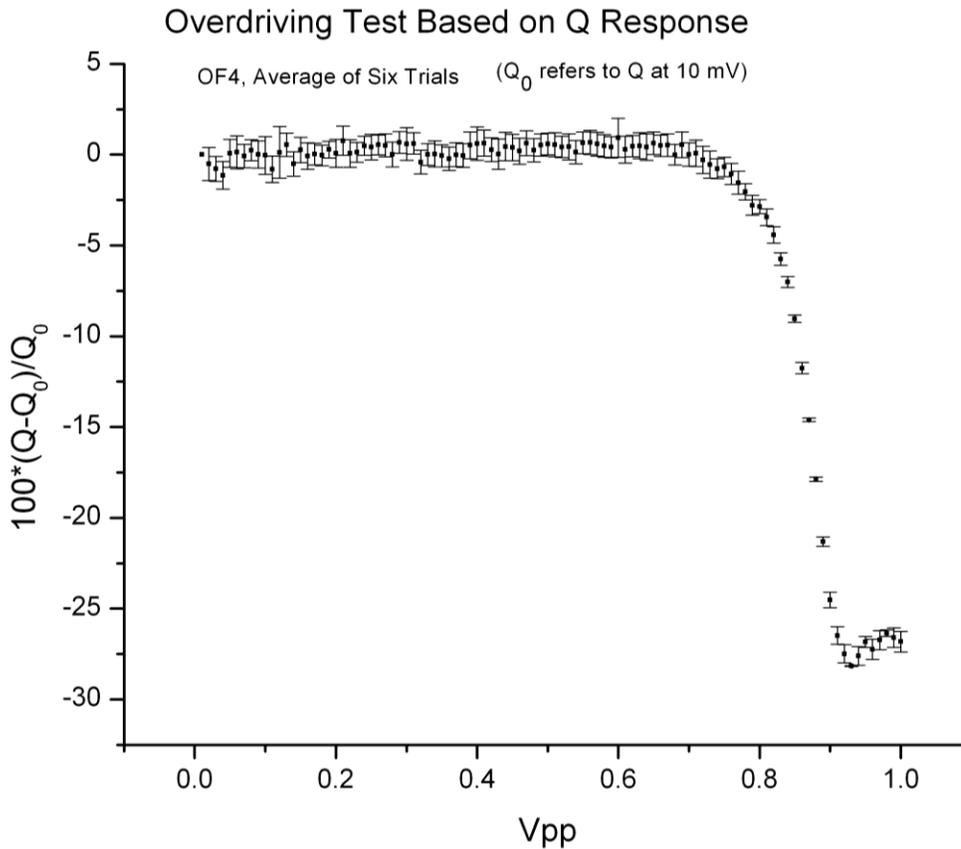


Figure 5: The overdriving test, showing the percent change in  $Q$  as the driving AC amplitude is increased on open fork number four, averaged over six trials. The  $Q$  value remains independent of the driving amplitude until roughly 600 mV, at which point it begins to respond nonlinearly and the shape of the resonance curve itself (not shown) changes. Care was taken to avoid this region.

base until the canister could be removed. Extreme care was taken in the removal and storage of the forks. The same resonance frequency measurements were then repeated, with ten runs through the magnet averaged in an attempt to acquire a reproducible background response from the magnetic field and increased dampening from air resistance (figure 6).

Ultimately, the forks were then loaded with ceramic magnet powder by carefully applying a drop of liquid-type Krazy Glue<sup>®</sup> to the tip of one tine of a fork, and then, with

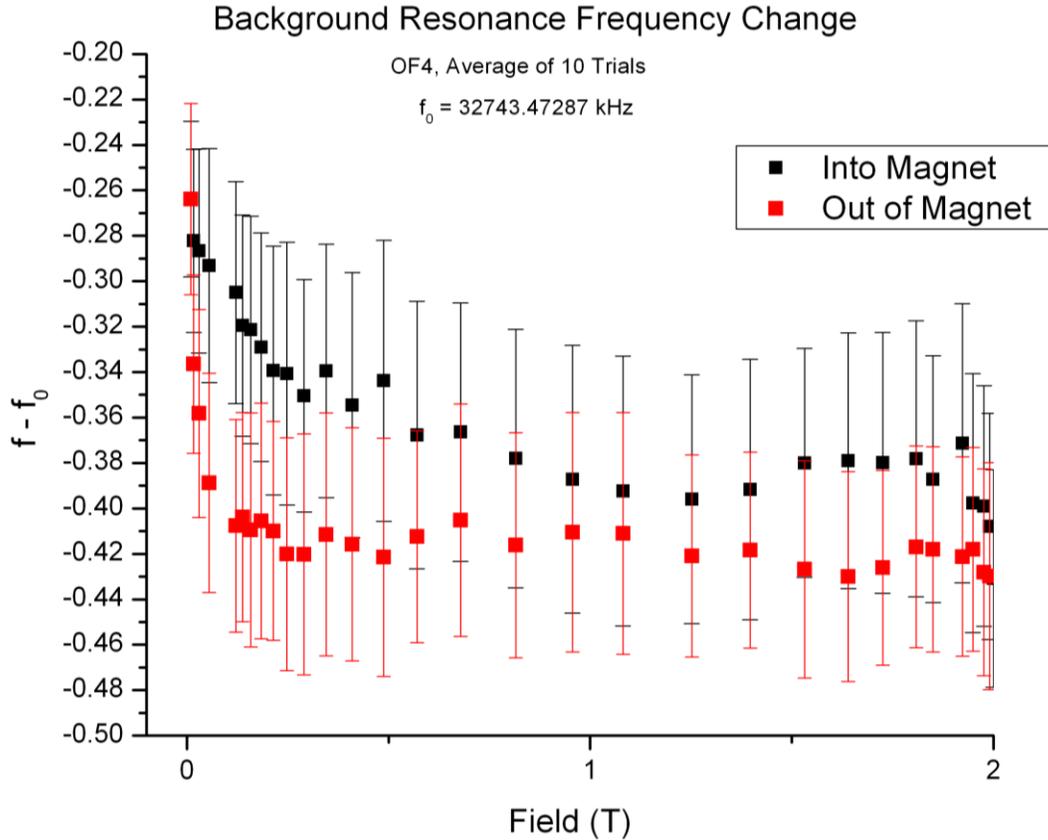


Figure 6: The change in resonance frequency of an unloaded fork (open fork four) in response to increasing and decreasing magnetic field, averaged over ten trials. At the end of the trial, the resonance frequency returned to its original value, forming a complete loop. The reproducibility of this precise pattern among other forks, and on the same fork once loaded, is still unclear however, and thus this signal could not be subtracted from the loaded fork measurements.

even more care, using a cotton swab to brush a small amount of the powder onto the glued area. The forks were then allowed to dry overnight for maximum stability in the resonance frequency measurements. The forks then had to be tested for resonance and  $Q$  response to ensure no damage had been done in the application process (manifested usually in an absence of resonance and visible cracks in the tines). Finally, the loaded forks were swept through the magnet, and the changes in resonance frequency analyzed (Figure 7). Temperature compensation was not used on loaded forks because they have much lower  $Q$

values than closed forks (the entire resonance curve spanning nearly 100 Hz as opposed to only a few Hertz) and the maximum effect of temperature (a difference of 0.5°C inside the bore of the magnet) is on the order of  $10^{-4}$  Hz, essentially negligible.

To look for the magnetic powder's coercive field, a loaded fork was then pre-magnetized against the field of the Oxford magnet, and then a run was done. Both channels were recorded to see whether the response from the X channel in the magnetic field would entirely mirror that of the Y channel, a confirmation that  $0^\circ$  is indeed the proper phase setting (figure 8).

### III. Results

Measurements of the  $Q$  response with respect to AC amplitude yield a nonlinear region beginning at roughly 600 mV, and thus care was taken to avoid such high driving amplitudes. However, while the unloaded forks produce a clear resonance signal at as low as 10 mV, loaded forks had to be driven much more strongly, around 500 mV, for a resonance to be visible above noise.

While protected in its canister, forks had  $Q$  values on the order of  $10^5$ , but were reduced to  $10^4$  upon exposure to air, and further to  $10^3$  while loaded with magnetic powder. With respect to the resonance frequency, exposure to air reduced  $f_0$  by about 20 Hz, and loading by over 1100 Hz, in rough agreement with past experimentation.<sup>4</sup>

The background data compiled from open, unloaded forks yielded a loop-like pattern, although individual runs displayed a high degree of variation even with temperature correction. Testing a loaded fork yielded somewhat similar results (Figure 7).

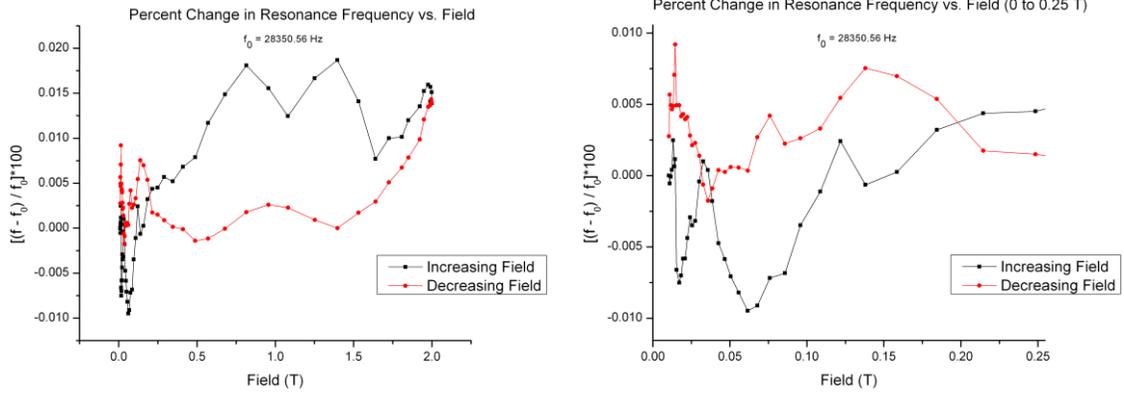


Figure 7: The percent change in resonance frequency of loaded fork five after one trial. A pattern similar to that seen in the open fork background test is seen, and perhaps a trace of the hysteresis segment the remnant magnetization and saturation points in figure 1.

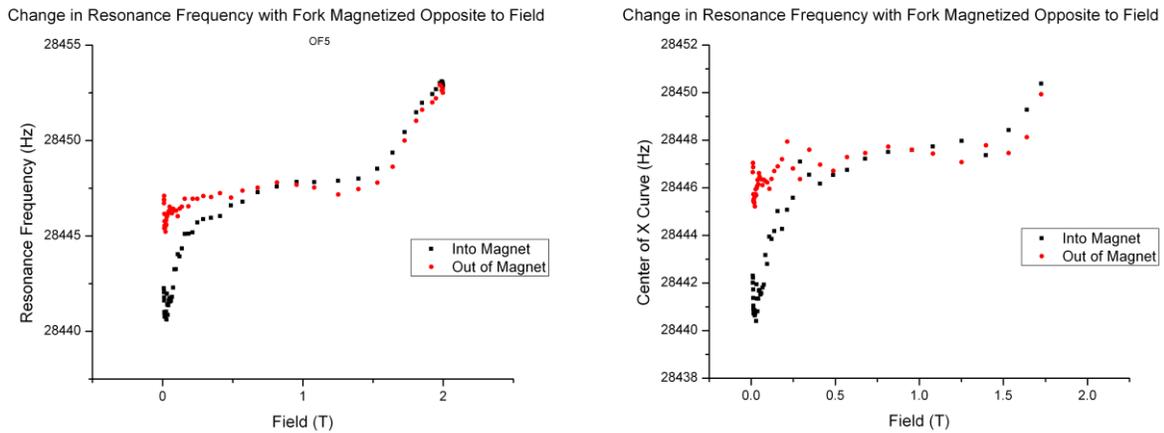


Figure 8: The X and Y responses (Y on the left, X on the right) to a magnet sweep with the fork pre-magnetized against the Oxford magnet. A rough estimation of the coercive field can be seen (between 0.125 and 0.5 T), as well as elements of the background signal (the “check marks” at the beginning and end of the dataset), but further research should be done to identify the cause of the high-field rise in resonance frequency after the fork seems to reach its saturation field. While X data was not taken for the highest field strengths, these two curves are nearly identical, assuring that a phase difference of  $0^\circ$  is ideal, in agreement with past findings,<sup>7</sup> and that either the X or Y channel could be used to test for resonance.

However, the fork that was pre-magnetized against the Oxford field displayed more convincing aspects of hysteresis and offered an estimate for the ceramic magnetic powder’s coercive field, between 0.125 and 0.5 T.

#### IV. Discussion

The mark of the open-fork background pattern was seen in the first test of the loaded fork, possibly due to magnetoresistance in the fork's magnet leads, but as this represented only one trial, more tests will be needed to determine the effect of error. However, the mark of hysteresis can perhaps also be seen, as the graph has a similar shape to the segment between the remnant magnetization and saturation in Figure 1, and indeed, the ceramic magnet powder had been magnetized before this test, having been through the magnet once before. The estimation of the coercive field from the fork pre-magnetized against the Oxford field is consistent with past measurements,<sup>8</sup> and though replication of these tests is needed to determine the effect of error on the data (and whether grinding the magnetic material into a powder altered its coercive field), these results show some promise for use of quartz tuning forks as magnetometers.

Questions remain with noise reduction, however. While unloaded forks entered a region of nonlinear  $Q$ -values around 600 mV, it is not clear whether such would still apply with loaded forks, as adding mass to the forks could fundamentally change their piezoelectric and thermal properties. Indeed, it is unknown whether the temperature correction formula used for closed forks would still be applicable for loaded forks. With regard to the hysteresis found in the background fork signal, it is unclear whether a saturating field was ever reached, and future studies with higher field strengths (higher than two Tesla) should be made, and if possible, the magnetic leads of the forks should be replaced with a conductor that does not display magnetoresistance. Additionally, the high degree of uncertainty in the background hysteresis, even when performed on one fork and averaged through ten trials, hints that each fork should be characterized for its background

signal before loading, and that more variables may in play than have been understood thus far. Only after further study of these background effects may the use of quartz tuning forks as magnetometers become feasible.

## V. Acknowledgements

I would like to thank the University of Florida Physics REU program (DMR-1156737) for allowing me to attain such invaluable research experience, and the coordinators who made this possible, from all the picnics to getting us paid: Dr. Selman Hershfield, Tim Schlittenhardt, and Ms. Kristin Nichola. Additionally, this project was supported by the NSF and grant DMR-1202033 to M.W.M. I would also like to thank Mathew Calkins, Pedro Quintero, Elisabeth Knowles, and Marcus Peprah for teaching me invaluable technical skills and for my myriad questions.

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