

Piezoelectric Quartz Tuning Forks as Room Temperature Magnetometers

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Abstract

Commercial piezoelectric quartz tuning forks are designed for sharp resonance oscillations at frequencies near 32.7 kHz. These forks are inexpensive and may prove to be effective magnetometers. Different forks of the same model were tested both in and out of the protective canisters. The forks were then loaded with magnetic nanoparticles and placed in a magnetic field. For a loaded fork, a dependency of the resonant frequency, f_0 , on the magnetic field is shown, but more analysis is needed to quantitatively answer whether the quartz tuning fork can be used as an accurate, inexpensive magnetometer operating at room temperature.

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I. Introduction

As the nanotechnology industry continues to grow, so does the need for reliable methods of measuring the magnetic properties of different nanoparticles. There are different methods for taking these measurements, most of which are costly and time consuming, creating demand for inexpensive, yet effective, methods. Small quartz tuning forks, starting at \$0.30 [1], may provide one such method.

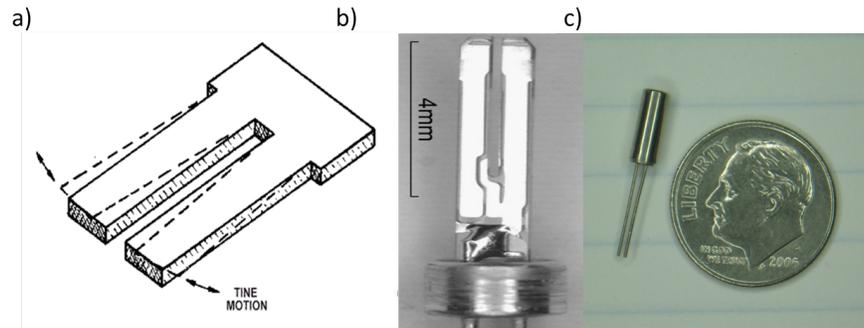


Figure 1: a) Schematic of a quartz tuning fork depicting the lowest mode of oscillation [2]. b) Magnified image of actual quartz tuning fork tines [3]. c) Photograph of quartz tuning fork in vacuum-sealed canister shielding tines from the company next to an American dime for scale.

A quartz tuning fork is two parallel tines connected at the base so that the structure is made of one solid piece of quartz. In the lowest mode of oscillation (the fundamental mode), each tine vibrates with an antinode at the tip and a node at the base, or bridge (Fig. (1a)). Each tine oscillates out of phase with each other in approaching and receding periodic cycles. Under small amplitude oscillations, the motion of each tine can be simplified to a one dimensional model. With a sinusoidal excitation, the equation of motion for the tip is

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

where the driving force (F_0) arises from applying a sinusoidal voltage across the leads of the tuning fork, x is the displacement of one tine along a line between the tines, m is the effective mass of one tine, β is the damping coefficient, and k is the spring constant of the tine [4]. The solution for Eq (1) can be written as $x(t) = x_a(\omega) \sin(\omega t) + x_d(\omega) \cos(\omega t)$ where x_a and x_d are the absorption and dispersion components, respectively, and are both functions of the driving frequency, ω [5]. The average absorbed power is at its maximum at the resonant frequency, $\omega_0 = \sqrt{k/m}$, with a quality factor of $Q = \omega_0/\beta$. This Q factor is the ratio of ω_0 to frequency width, $\Delta\omega$. of the resonance curve at half of the maximum power [5]. From the factory, quartz tuning forks are sealed in vacuum conditions by a protective canister (Fig. 1c) [5]. Because drag is minimal in the canister due to low pressure, i.e. low β , the Q for the tuning forks is relatively high ($\sim 10^5$, as shown sec. **III.**).

Due to the piezoelectric effect, these oscillations of the tines induce charges and cause a current that is proportional to the velocity of the tip of the tine, allowing for the fork to be modeled as an RLC circuit. The equivalent equation of motion is

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

where $V(t)$ is a sinusoidal driving voltage, R is resistance, L is inductance, and C is capacitance. By comparing Eqs. (1) and (2), we see that $\omega_0 = 1/(LC)$, $\beta = R/L$, and $I(t) = I_a \cos(\omega t) + I_d \sin(\omega t)$. Similar to the mechanical analog, $I_a(\omega)$ and $I_d(\omega)$ (Fig. (2)) are the absorption and dispersion components of the current respectively with theoretical resonance curves,

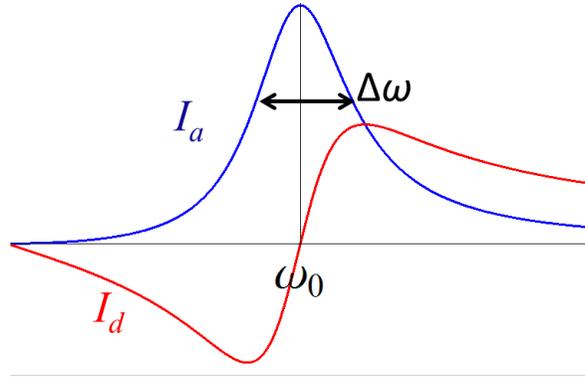


Figure 2: Theoretical absorption, I_a , and dispersion, I_d , curves. The peak of I_a occurs at ω_0 while the full width at half maximum yields $\Delta\omega$.

$$I_a = \frac{I_0(\Delta\omega)^2\omega^2}{(\Delta\omega)^2\omega^2 + (\omega^2 - \omega_0^2)^2} \quad (3)$$

and

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

The absorption component, $I_a(\omega)$, peaks at a value of I_0 at resonance, $\omega = \omega_0$, and the full width at half maximum of this curve gives $\Delta\omega$ [5,6], and therefore Q of the resonance curve.

II. Experimental Details

An Agilent 33220A function generator was used to provide a sinusoidal voltage to one lead of the quartz tuning fork while the other lead was held at a virtual ground by an LF411 op amp with a negative feed back loop. The function generator was then set in sweep mode in order to provide voltages at different frequencies. The current through the piezoelectric quartz tuning forks was then measured with an SR530 lock-in amplifier via measuring the voltage across the 1 k Ω resistor in the feed back loop of the op amp (Figs. (3) and (4)). The phase sensitive lock-in is able to separately measure the absorption (X channel) and

dispersion (Y channel) components of the voltage that are at the frequency of the function generator (Fig. (5)). The SR530 has an adjustable phase difference setting, and to test which setting the phase difference needed to be, a sweep was run with phase differences ranging from 20 to -20 degrees at 5 degree intervals. The resulting curves were plotted as X channel vs Y channel. A local minimum can be observed at 0 degrees and this setting was deemed sufficient (fig. (6)). There were two different models of 32.7 kHz quartz tuning forks available in the lab, big and small. The big forks were used because their size facilitated the removal of the protective canister. The forks still in the canisters are denoted as BCF while the tuning forks with the canisters removed are denoted as BOF.

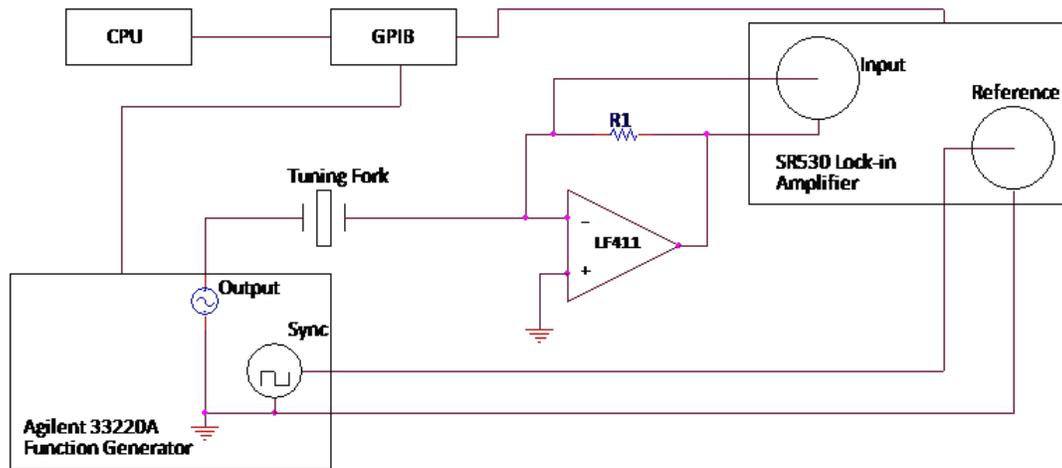


Figure 3: A function generator provides a sinusoidal voltage to the tuning fork and a LF411 op amp with a negative feedback loop is used in conjunction with the lock-in amplifier to isolate and measure the voltage drop across the fork. The resistor value used : $R1 = 1 \text{ k}\Omega$.

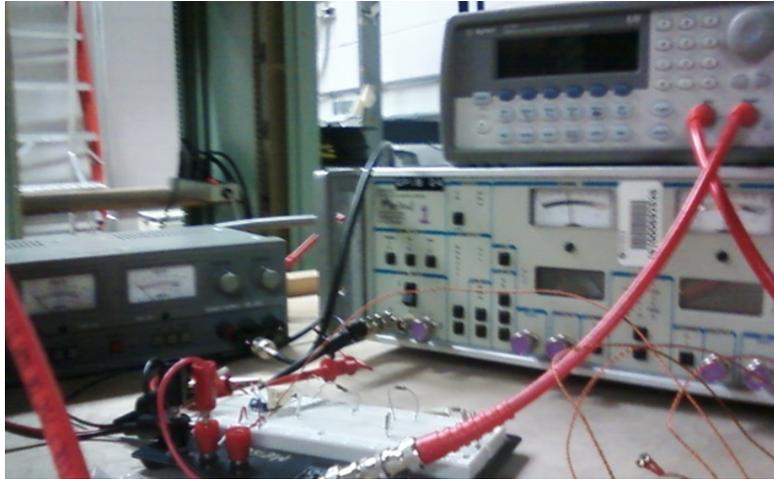


Figure 4: The power supply for the op amp and the Agilent33220A function generator sitting on top of the SR530 lock in amplifier along with the wired circuit. A twisted pair of wires with a piece of a slotted IC soldered to the end is used in sweeping the magnetic field with the tuning forks.

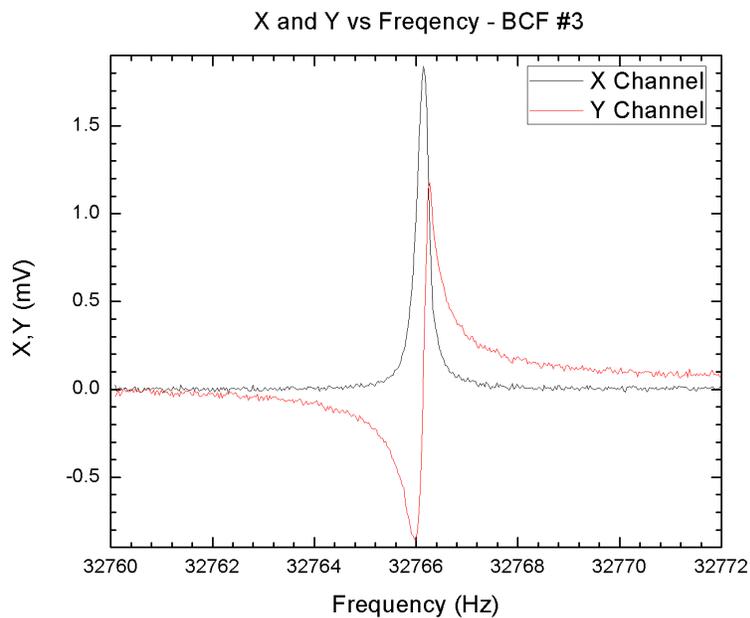


Figure 5: The absorption (X channel) and dispersion (Y channel) curves for a tuning fork still in the canister (BCF) with a driving force amplitude of $V_0 = 50 \text{ mV}_{pp}$ and a Y offset value of 1.7 mV used to center dispersion curve near zero.

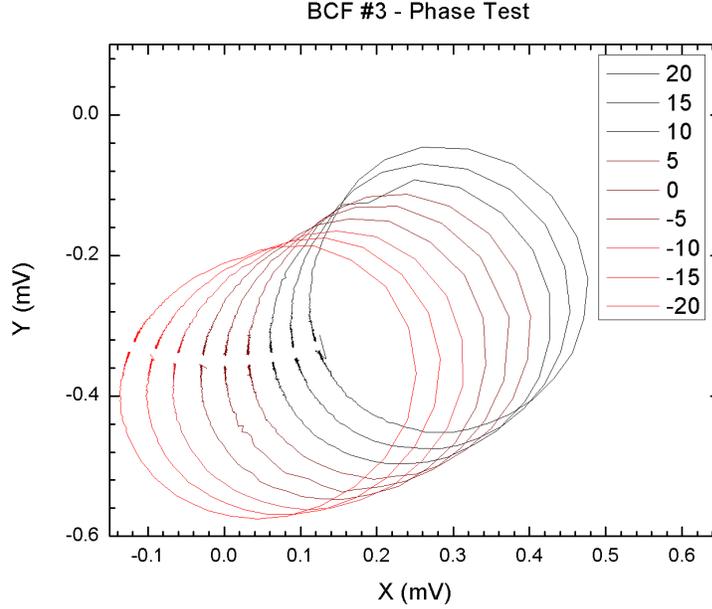


Figure 6: Y channel vs. X channel plots for BCF #3 at varying phase difference, ϕ , settings of the lock in amplifier. Notice the local minimum at $\phi = 0$. This suggests that $\phi = 0$ is the setting for the lock-in that yields pure absorption and dispersion curves rather than a mixture of the two. The above resonance curves were obtained with a 10 mV_{pp} driving voltage and no offsets in either channel.

After sweeping through a range of frequencies that contained the resonant frequency, $f_0 = \omega_0/2\pi$, for a quartz tuning fork still in the protective canister, the canister needed to be removed, which was achieved by clamping the canister in a pair of hemostats and filing the edge of the canister until the fork and glass disc holding the leads were almost free. The leads were then grasped using a small pair of needle nose pliers or dikes and gently pulled and slightly twisted until the fork and glass disc were free from the canister. The exposed fork is then placed into a slotted IC for safe handling (Figs. (7) and (1b)). Since the quartz is fragile and breaks easily, extreme care in handling is needed once the tuning fork is free from the canister.

With the fork's protective canister is removed, a frequency sweep was performed once again to measure the resonance, or response, curve in order to observe the effects of drag from



Figure 7: Quartz tuning fork after the protective canister has been removed by filing the the lead end of the canister until the fork is able to be pulled free from the canister. Removing the fork in this fashion allows the protective glass disc to remain intact and protect the leads from breaking off from the fork itself. The dime is in place for scaling.

air resistance. The fork also needed to be tested in order to determine if it was damaged during the removal of the protective canister. Looking at the fork under magnification revealed any major cracks in the quartz. A frequency sweep through resonance at varying phase differences also tested the integrity of the fork (Fig. (8)). More comparisons of damaged and undamaged forks are made in sec. **III.**

The next step was to apply magnetic nanoparticles to the open fork by applying a small amount of Krazy Glue[®] to one of the tines and then sprinkling a small amount of MnZn ferrite powder over the freshly applied glue. To ensure nanoparticles did not short circuit the fork, the continuity was tested across the leads with an ohmmeter. Once nanoparticles were glued to one of the tines of the tuning fork, it was set aside to dry overnight. The tuning fork was again tested for a resonance. After finding the resonance frequency, the fork was placed in different magnetic field strengths created by an Oxford 9T magnet set to $H_0 = 2\text{T}$ to measure any dependency on magnetic field of f_0 and Q .

After obtaining resonance curves for tuning forks in and out of the protective canisters, the absorption data was fit with a Lorentzian function using Origin. From this fit, values for f_0 , Δf , and the respective uncertainties, and therefore Q , were extrapolated.

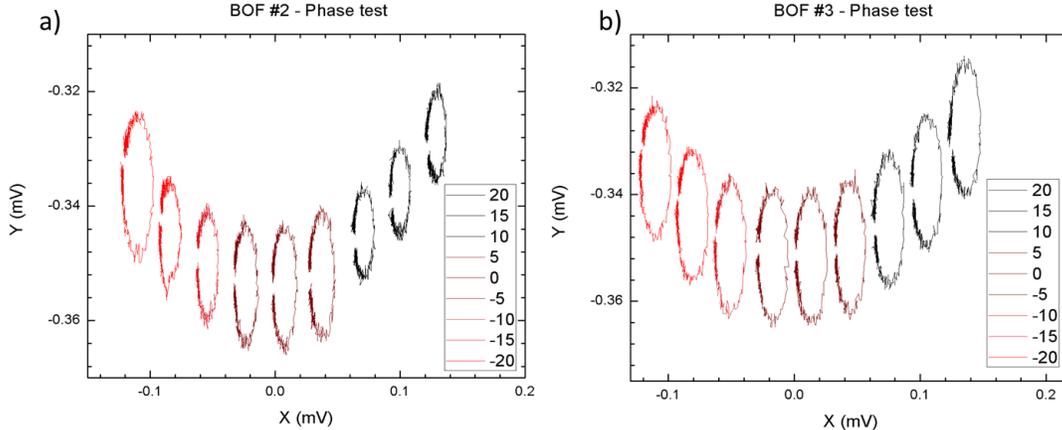


Figure 8: Applying a frequency sweep to an open fork at varying phase difference will determine if a fork has been damaged during the removal of the protective canister. In a) is a suspected damaged fork while b) is a fork that appears to have not been damaged. Notice in b) that the structures are all of similar size and shape but this is not the case in a). The different structures vary in size at the various phase difference settings of the lock-in amplifier.

III. Results

After removing the canister, a shift in f_0 was observed as well as a significant decrease in Q (Fig. (10)). These results yield a drop in f_0 of 8-13 Hz (Table (1)) where past results from Lunts et. al show a shift of 6 Hz [7]. BOF #2 had an outlying value for f_0 suggesting this fork was damaged during removal of the protective canister. Also, the Q drops an order of magnitude due to the air resistance, though the diversity of these values for Q suggest that f_0 will be the important for using quartz tuning forks as magnetometers.

Once the MnZn ferrite nanoparticles were applied, the fork needed to be driven with a higher voltage sine wave for the resonance curve to be seen. Rather than the prior 10 mV_{pp}, the loaded fork was driven with a 500 mV_{pp} in order to measure a resonance curve that was above noise. These data showed another drop in f_0 and Q (Fig. (11)) such that $f_0 = (31650 \pm 1)$ Hz and $Q = 490 \pm 30$. This result shows more than an 1100 Hz drop in f_0

Table 1: Resonance Frequencies and Quality of Closed and Open Forks

Fork	f_0 (Hz)	Q
BCF #3	$32766.041 \pm .001$	$(1.26 \pm 0.02) \times 10^5$
BOF #2	32753.71 ± 0.02	$(7.8 \pm 0.1) \times 10^4$
BOF #3	32756.08 ± 0.02	$(7.8 \pm 0.1) \times 10^4$
BOF #4	32758.52 ± 0.06	$(7.1 \pm 0.3) \times 10^4$
BOF #5	32758.09 ± 0.06	$(8.9 \pm 0.4) \times 10^4$

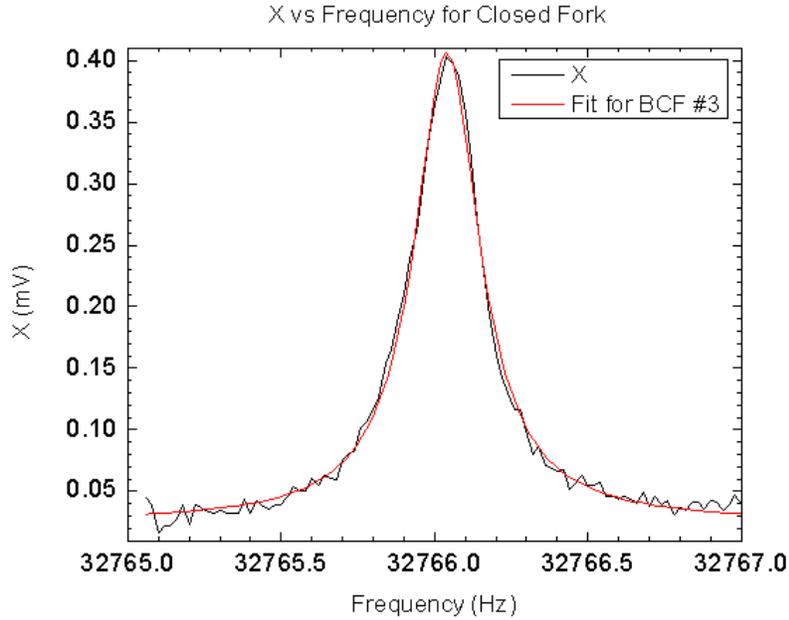


Figure 9: Absorption curve for BCF #3 in zero H field with Lorentzian fit curve superimposed. Values of $f_0 = (32766.041 \pm .001)\text{Hz}$ and $Q = (1.26 \pm 0.020) \times 10^5$ are extrapolated from fit.

from the unloaded forks and a drop in Q of two orders of magnitude from the unloaded fork. No forks were tested for resonance with just Krazy Glue[®] and no MnZn ferrite nanoparticles loaded on a tine.

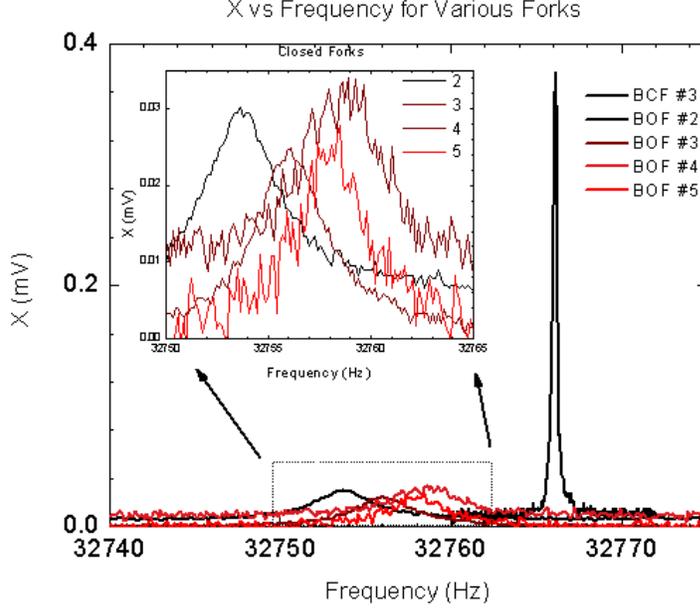


Figure 10: Absorption curves for one fork still in the canister (BCF #3) and 3 forks with their canisters removed (BOF #2-5) showing a shift in f_0 of 8-13 Hz. The Q value has also dropped an order of magnitude for the closed forks (Table (1)). With f_0 of BOF#2 being outlier, this fork was likely damaged during removal of its canister.

With f_0 and Q determined, the loaded fork was swept through increasing and decreasing magnetic fields in steps of 0.1 T. f_0 and Q were extrapolated from the Lorentzian fit at each point in the field to determine any dependence on magnetic field. A strong dependency is shown for f_0 as H is increased and then decreased (Fig. (12a)). There is no clear correlation between Q and H (Fig. (12b),) confirming that f_0 is the important value to consider for using quartz tuning forks as magnetometers. For comparison, the bare BOF #2 was also swept in and out of the magnet. Although this fork, which appears to be slightly damaged, did not produce a resonance once MnZn ferrite nanoparticles were applied (Figs. (8a) and (10)), this lack of dependency suggests that the hysteresis feature of Fig. (12a) is not a manifestation of magnetic leads but rather a result of the MnZn ferrite nanoparticles.

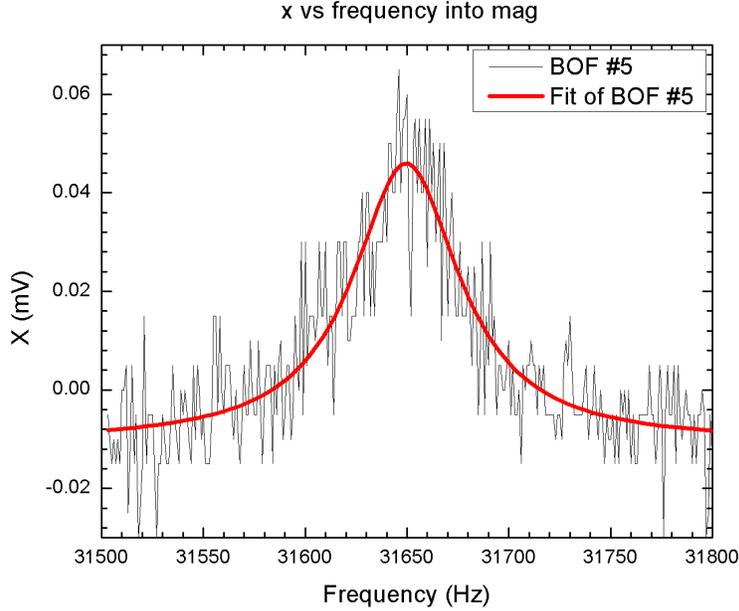


Figure 11: Response curve and fit line for open fork loaded with MnZn ferrite nanoparticles. After applying the particles with Krazy Glue[®], this fork needed to be driven with a higher voltage than before the particles were added to yield a response curve above noise (500 mV_{pp} compared to the 10 mV_{pp} from prior to the nanoparticles were applied). Adding the nanoparticles decreased resonance frequency by more than 1100 Hz such that $f_0 = (31650 \pm 1) \text{ Hz}$ and Q dropped by two orders of magnitude, $Q = 490 \pm 30$.

IV. Discussion and Future Work

There is no dependency of H for Q shown for the loaded fork, and therefore Q should not be the value to focus on for future work, but the data of f_0 vs H shows promise for a hysteresis loop. MnZn ferrite is a soft ferromagnetic material, and the hysteresis loop is narrow and has a low coercive field, but also has a low saturation value, $H_{sat} \approx 0.5 \text{ T}$ (Fig. (14)), showing that a quartz tuning fork will resonate with magnetically saturated material loaded on one of the tines. This finding, combined with the potential of a hysteresis loop in f_0 vs H , show piezoelectric quartz tuning forks to be strong candidates as a room temperature magnetometers.

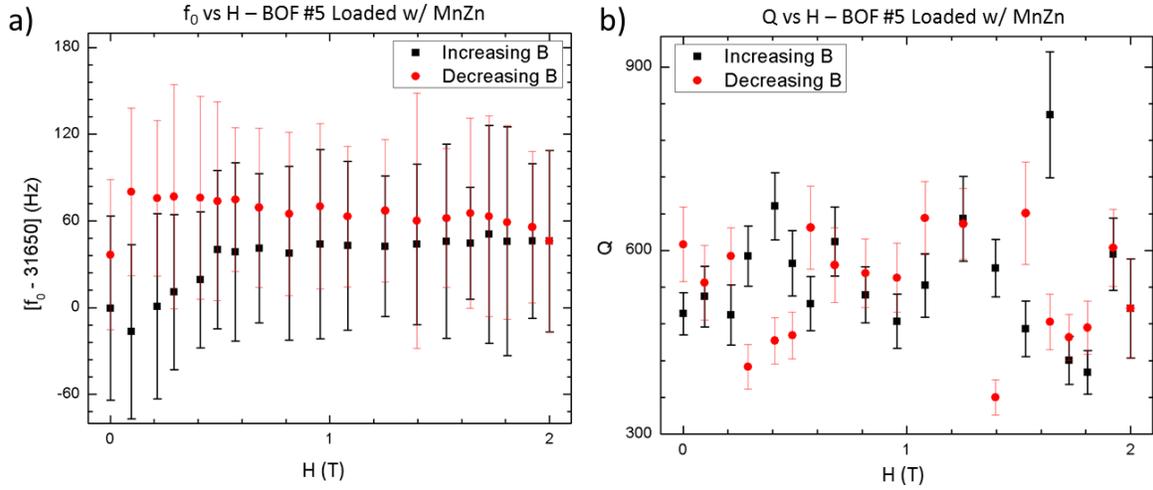


Figure 12: Dependency of f_0 (a) and Q (b) on H where the black squares and the red circles represent increasing and decreasing magnetic field strength respectively. Notice in (a) the hysteresis-like feature as the fork is lowered into and lifted out of the magnet. This result shows promise for the quartz tuning fork to be used as a magnetometer. (b) shows that there is no dependency on H for Q , and therefore Q should not be the value to focus on for future work. The uncertainty bars come from Origin's uncertainty in the Lorentzian fit.

One question left unanswered is whether or not the dependency of the resonant frequency on magnetic field strength comes from the nanoparticles or from the the magnetic leads of the tuning fork. If future work finds that this dependency is a direct result from the leads, then the leads will need to be removed and non-magnetic leads will have to be attached. Another issue that will require attention is reproducibility of the bare open forks resonance curves. More forks will need to be opened and response curves compared. Also, in order to quantify any results from the tuning fork, the mass of the nanoparticles added to the tine of the fork will need to be determined with some level of accuracy.

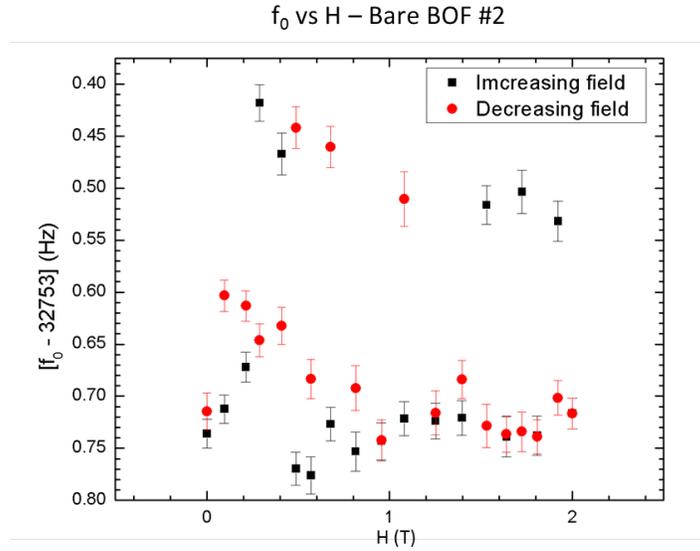


Figure 13: f_0 vs H for an unloaded open fork showing no dependence on H . Even though this fork did not produce a resonance once nanoparticles were applied and is believed to be damaged (Fig. (8a)), this suggests that the hysteresis feature from Fig. (12a) is not a manifestation of the magnetic leads of the fork.

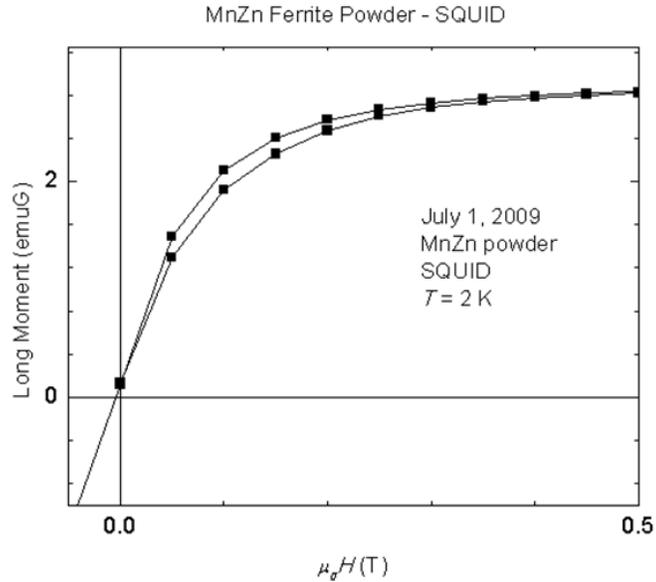


Figure 14: SQUID data for MnZn ferrite powder taken at 2 K in 2009. These data show MnZn to be a soft ferrite with low coercive field and saturation values, $H_{sat} = 0.5$ T. Finding a response curve for a loaded fork at 2 T confirms that resonance of the tuning fork is possible under magnetically saturated conditions.

V. Acknowledgments

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