QZFM Linearity

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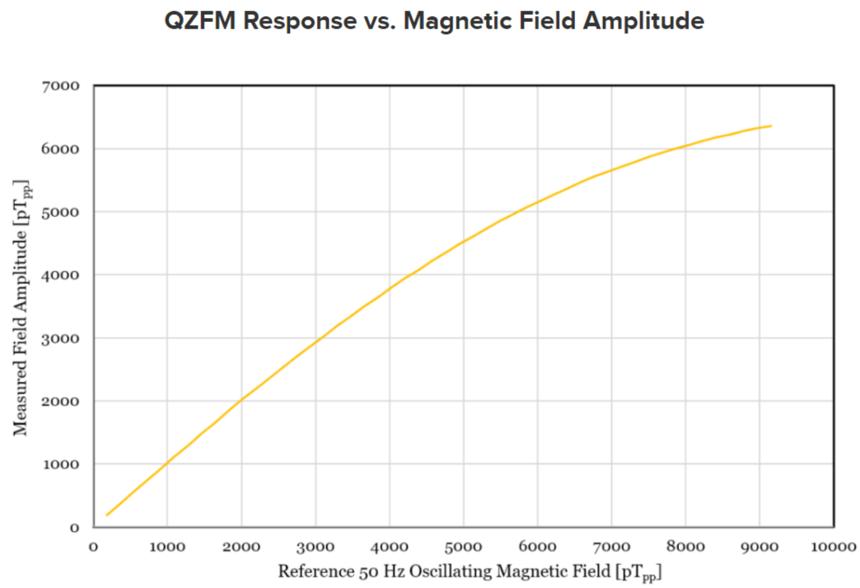

Figure 1: QZFM linearity at 50 Hz according to Quspin. Which axes this depicts is not made clear.

1 Introduction and Motivation

The Quspin Zero Field Magnetometer (QZFM) is to be used to measure the absolute ambient field within the large magnetically shielded room (MSR) for the planned nEDM experiment at TRIUMF, which requires a very low magnetic (significantly lower than 1 μT) amplitude and a very small magnetic gradient. The intended operation procedure is as follows:

1. The QZFM will start at some initial position (e.g., the center of the MSR), and is zeroed at this position, yielding three readouts from the internal compensation coils that physically represent the negative of the absolute ambient field vector components. The readouts will have the internal systematic sensor offsets subtracted. The cell reading at this point will have zero offset.

2. The QZFM is then moved to some other location, *without* re-zeroing. This is because zeroing restarts the internal PID controls, yielding about 20 pT of variability in the compensation readings (this is a result of a previous study of the QZFM offsets), which is too large for the accuracy we seek.

3. Instead the cell is read directly. Since the QZFM has now moved in a magnetic gradient but the compensation coils are still locked to the earlier values, the cell will now have some amount of non-

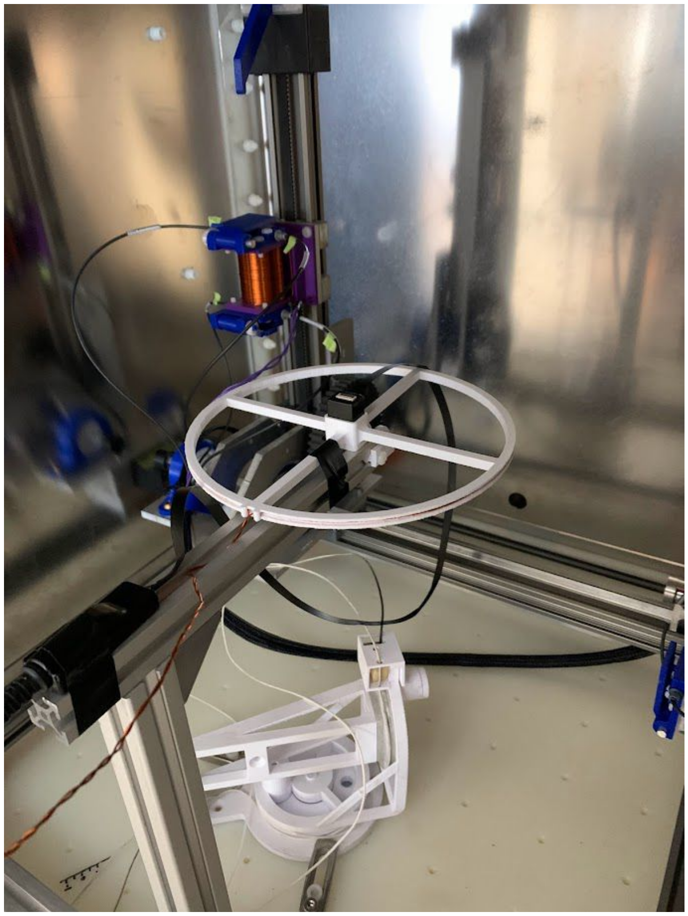

Figure 2: The single turn loop with the QZFM cell at its center. In the pictured configuration the z-axis of the sensor is aligned with the field direction.

zero mean value. From this new mean value, the absolute magnetic field can still be obtained as $\mathbf{B} = -\mathbf{B}_{\text{coil}} + \mathbf{B}_{\text{cell mean}}$

Therefore, it is important to know the linearity of the cell readings with varying field amplitude. According to Quspin's website, the linearity at 50 Hz behaves as in Figure 1. To quote Quspin, the QZFM is linear up to 1 percent up to 1 nT, which agrees with the curve shown. The goal of this study is to produce a similar curve as Figure 1 for the QZFM sensor in-house at TRIUMF, from which it will be possible to work backward from the measured value to the true value.

2 Apparatus and Methods

The QZFM requires a near-zero background field to operate, and the center of the mini-MSR satisfies this condition. To generate the magnetic field, a single-turn circular loop with a diameter of 170mm is used. See Figure 2 for a photo of the setup mounted within the MSR. The mount is made out of aluminum extrusions, but since we are only interested in near DC frequencies, the Eddie current effects are negligible. Since only one axis can be aligned with the field direction at the center of the loop, three separate loops with the central module adapted are made.

The magnetic field was generated using a Rigol DG1032Z function generator, in the form of sinusoidal waveforms. The raw signal output from the function generator is passed through a simple first-order high-

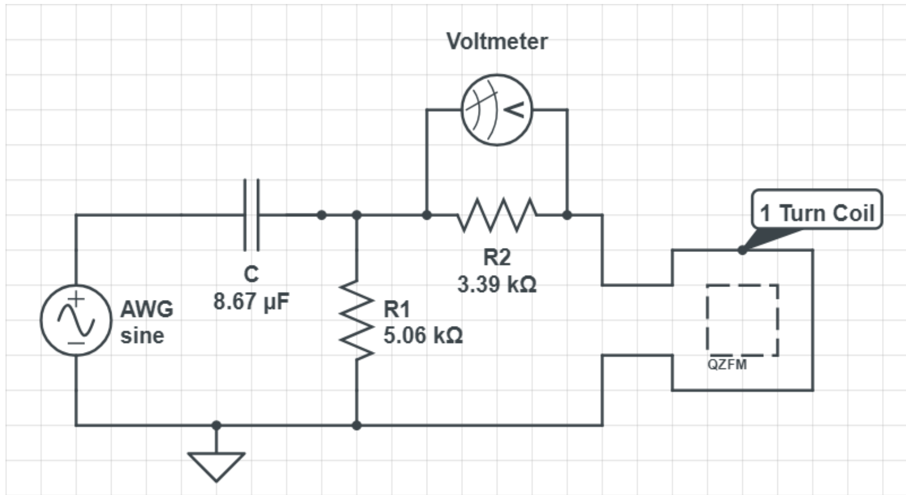

Figure 3: Diagram of the measurement circuit. The signal generated by the arbitrary waveform generator is first passed through a high-pass filter to eliminate any potential offset. The filtered signal voltage is monitored with a digital multi-meter across a second resistor R_2 in series with the main loop centered around the QZFM.

pass filter composed of a resistor with resistance $R = 5.06 \pm 0.06$ kΩ and a capacitor with capacitance $C = 8.67 \pm 0.01 \mu$F giving a -3dB cutoff frequency of

$$f_c = \frac{1}{2\pi RC} = 3.63 \pm 0.04 \text{ Hz}$$

The purpose of the high-pass filter is to eliminate any residual offset from the function generator. The high-passed signal then goes into the second part of the circuit consisting of the single-turn loop and a second resistor with resistance $R = 3.39$ kΩ, across from which a Keithley DMM6500 digital multi-meter is connected in parallel to measure the AC RMS voltage in the coil.

The measurement method is as follows:

1. The impedance of the circuit is calculated and set into the function generator, according to the formula for an RC circuit, and here the resistance is taken to be the equivalent resistance of the two resistors in parallel.
$$|Z| = \sqrt{R^2 + \frac{1}{(2\pi fC)^2}} \tag{1}$$

2. The QZFM receives command to turn on its compensation coils to null the background field at the cell location for 8 seconds. This time is sufficient for the coils to converge in the mini-MSR, but if this experiment is repeated in a different environment the zeroing time need to be checked. At the end of the zeroing time, the coils are commanded to hold the steady values and stop actively compensating.

3. The function generator outputs a sinusoidal signal with 0 offset, frequency of 35 Hz (see Appendix A for a discussion on why frequency matters.), and some amplitude. For consistency, we will understand amplitude in this study to mean peak-to-peak amplitudes.

4. The multi-meter reads the AC RMS voltage across the resistor in the loop part of the circuit (R_2 in fig. 3). The value is saved. One can chose to convert the RMS value to a peak-to-peak value by the conversion factor $2\sqrt{2}$, but this assumes a perfectly non-distorted sine wave along with trusting the calibration of the multi-meter. Luckily this does not matter for our analysis as will be seen later on.

5. The QZFM cell is read via its analog output and acquired using a LabJack T7 data acquisition unit. Only the single channel perpendicular to the plane of the loop is read, at a sampling rate of 10 kHz. The measurement lasts 5 seconds. This length of time is thought to be a good balance between allowing sufficiently high number of periods of signal oscillation for statistical certainty in the analysis on the one hand, and not too long for the freshly achieved zero field to be destroyed by drifts.

6. The measured file is saved, and the measurement repeats from step 2 for a higher input voltage amplitude.

The collected data is analyzed as follows:

1. A particular time trace corresponding to some input voltage is considered. For our purposes, the signal is composed purely of two parts, the 35 Hz oscillation and all other are noise. It is desired to extract the amplitude of the 35 Hz oscillation, which may be done in principle using a find peak algorithm such as the one implemented in the Python Scipy library, but this naive implementation will always overestimate the amplitude because the algorithm will always identify as maxima the locations where the noise is in phase with the oscillation, making the estimated crests larger and the estimated troughs smaller than the true values.

2. Instead, the peak finder algorithm is used only as a first step. All maxima and minima are roughly located and their indices are recorded. For each maximum and minimum a segment centered on the extrema and extending outwards by one-eighth of the period of oscillation on both sides, which in units of samples is given by $T_{\text{samples}} = f_s/f$ where f_s is the sampling frequency of 10 kHz and f is the oscillation frequency, at 35 Hz.

3. Each segment is fitted with a 4th order polynomial in the form $p(t) = ax^4 + bx^3 + cx^2 + dx + e$. The polynomial fit over what is in total one quarter of the oscillation period will be significantly less sensitive to noise, which tends to have much higher frequencies.

4. Iterating through all indices returned by the find peak algorithm, save the maximum/minimum values of the *polynomial fit*.

5. Finally the peak-to-peak amplitude is found by taking the average of the successive differences in the interweaved maximum/minimum data array.

6. repeat steps 1 to 5 for all time traces corresponding to all input voltages measured.

The key steps of the recipe are depicted in Fig. 4, where on the left an example time series is shown with all maxima and minima identified, and the right inset plot shows an example curve fit in the dashed red line. The actual maxima value is taken to be the maxima of the fit.

At this point, one can plot the input voltage vs. peak-to-peak measured magnetic field, but this curve is not really useful since it is in a sense not normalized. This is because for the same input voltage what the QZFM will measure is dependent on myriad things such as coil geometry, alignment of the sensing axis with the actual field generated, calibration of the voltmeter, etc. So it is useful to convert the input voltage to the input magnetic field value at the sensor location. To do this, one very important but reasonable assumption has to be made: **For the region where the QZFM is linear, the AC amplitude reported by the QZFM corresponds exactly to the actual background AC field amplitude it experiences.** Taking this crucial assumption, we can proceed as follows:

1. The initial few data points on the input voltage vs. peak-to-peak measured magnetic field graph will be linear. This is verified by curve fitting a linear function of the form $y(t) = mt + b$ to the data and checking the residual has no major discernible trend. The offset parameter b is only included for completeness, but we expect it to be almost zero. An example is shown in Fig. 5.

2. Because we assumed that in the initial region the value measured by the QZFM corresponds 1-to-1 with the actual physical field at the cell location, the relationship between the input voltage and the input magnetic field is simply a factor of m. (Here already we discard the offset b).

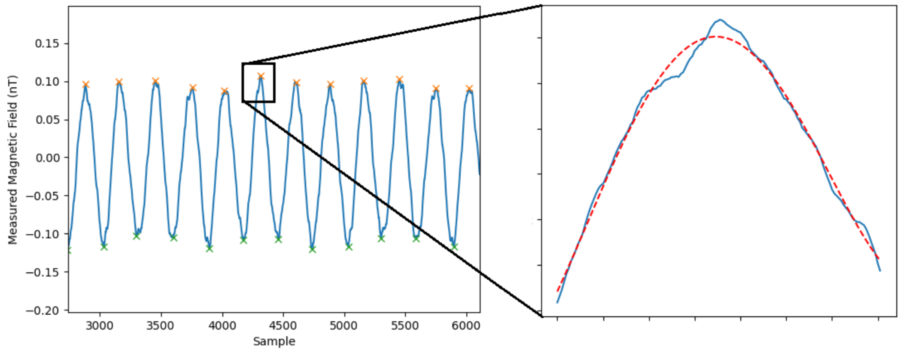

Figure 4: Example of the analysis recipe. On the left plot an example time trace of raw recorded data contaminated with noise is shown. The Scipy peak finding algorithm was applied and the rough locations of all crests are marked by orange Xs and all troughs are marked by green Xs. For each extrema, a segment ranging one-eighth period before the extrema and continuing one-eighth period after the extrema is cut and fitted by a 4-th order polynomial. The maxima/minima of the fit is taken to be the noise-adapted extrema value.

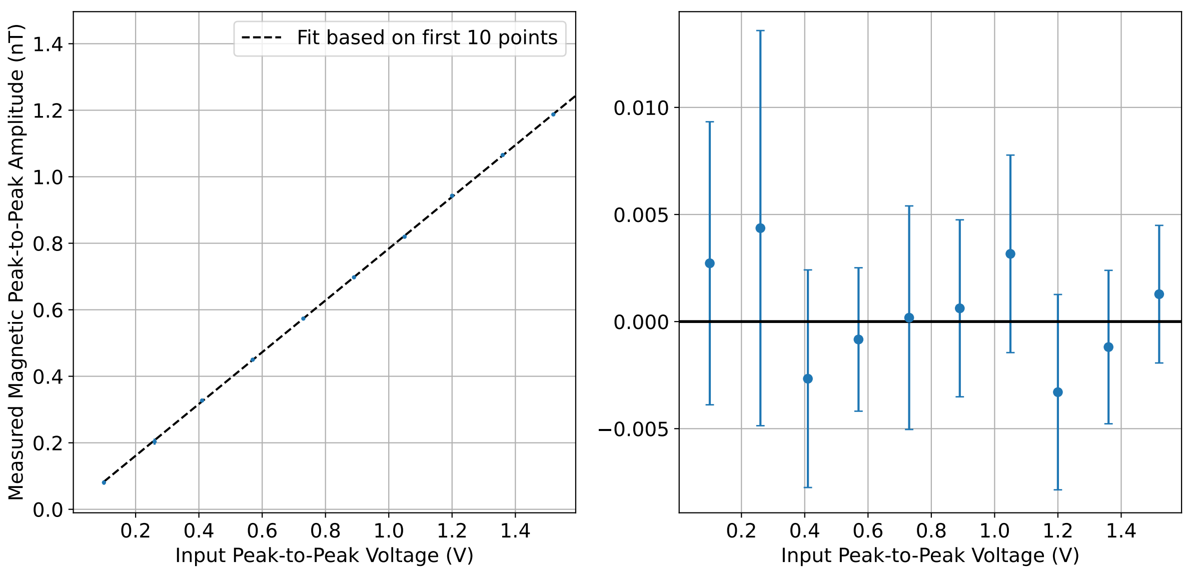

Figure 5: Left: An example linear curve fit of the raw input voltage vs. measured magnetic field data based on the first 10 data points to find the conversion factor between the input voltage and the actual generated magnetic field. Right: The residual of the fit. The fit is very healthy as all points are scattered without any overall trend about zero, and all data points lie within one standard deviation from zero.

3 Results

The procedure outlined above was carried out for all three axes of the QZFM AAL9 sensor and the results are plotted in Fig. 6. The corresponding CSV file will be made available on Plone for future reference. The degree of non-linearity is not uniform among the three axes, with the most severe non-linearity in x, followed by z and y. A reference perfect linearity line is provided for reference. The right subplot shows the absolute fractional deviation from perfect linearity, given by

$$\text{Abs Frac Dev} = \left| 1 - \frac{\text{Measured Value}}{\text{Input Value}} \right|$$

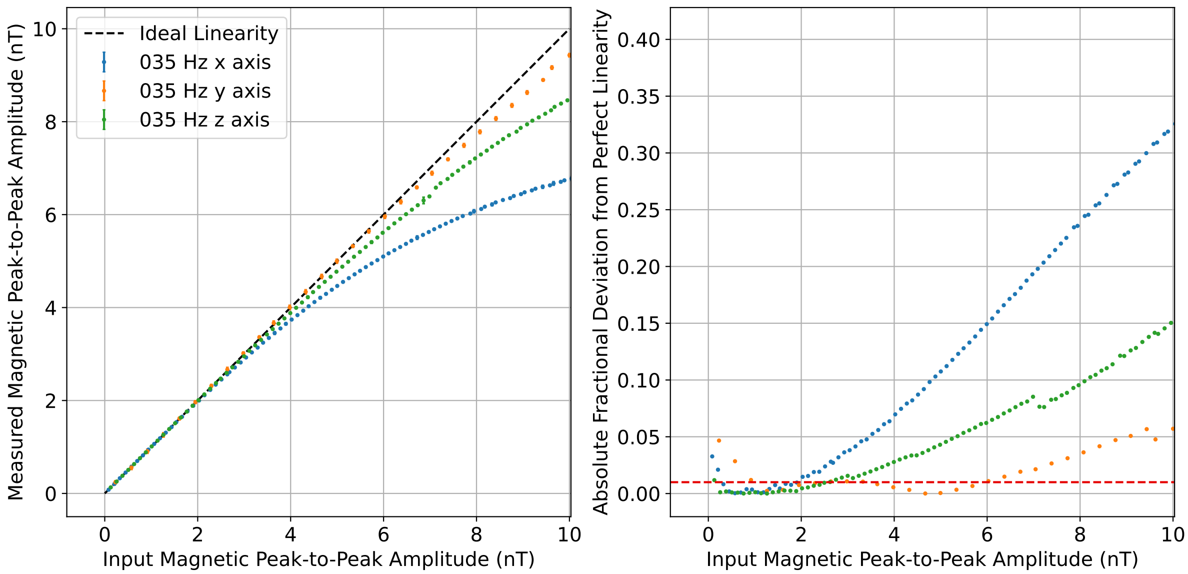

Figure 6: Left: Non-linearity of the tri-axial QZFM AAL9 sensor. Black dashed line is perfect linearity. Right: Absolute fractional deviation from perfect linearity for the three axes.

A Frequency Dependence

Since the method outlined in this report is centralized on measuring AC magnetic fields, the frequency is a key parameter to consider. According to Quspin's website, their sensor behaves as if there is a first-order low-pass filter with a roll-off at approximately 150 Hz. Actually, upon checking the response with a frequency sweep between 1 Hz and 500 Hz (top of fig. 7), we see the frequency-dependent roll-off starts to be significant already at 100 Hz. The roll-off is not due to impedance mismatch during the sweep, as we can calculate the changing impedance according to Eq. 1 in the sweep domain, as plotted in the bottom of Fig. 7. In the initial section where the impedance sees significant change, the output amplitude remains fixed, but it is only after 100 Hz when the impedance has reached equilibrium that the measured amplitude starts to drop.

Comparing the input voltage vs. measured magnetic amplitude curves for several frequencies between 1 and 500 (fig. 8), we indeed see that as frequency increases the QZFM becomes less sensitive to the same input voltage. Note in this case all trials are conducted with the same coil setup, therefore it makes sense to compare values along different curves at the same input voltage. Since for the ultimate use case the QZFM is to measure DC or very near-DC magnetic fields, it is necessary that the frequency we pick is sufficiently low to be useful. According to the sweep, but also confirmed by fig. 8, at least up to 50 Hz the frequency response is flat.

B Sensor AAY4 and Plone Folder Location

The same experiment was carried out for a second pair of QZFM gen 3 sensor, with serial number AAY4. The summary results are shown in fig. 9

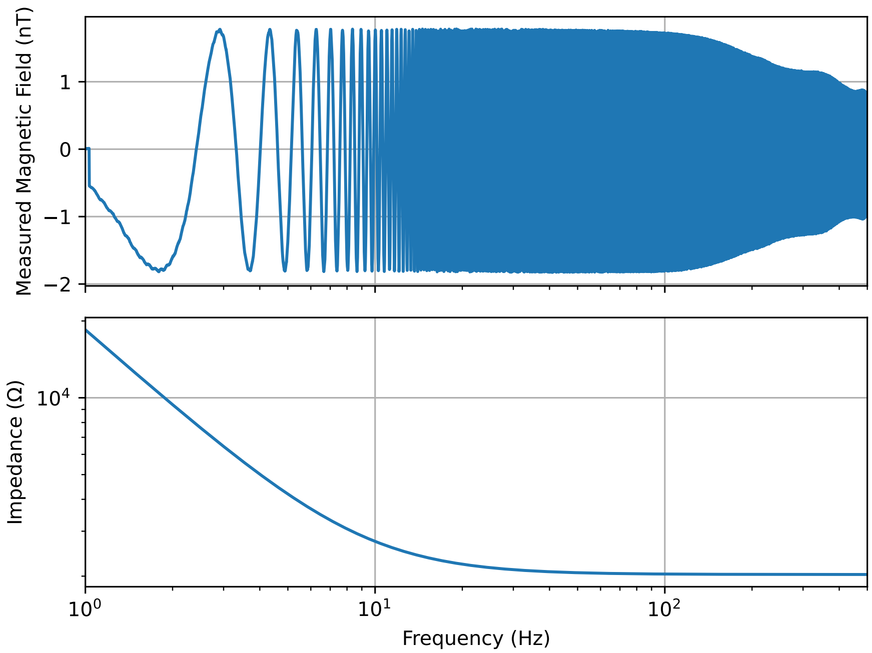

Figure 7: Top: QZFM response to frequency sweep between 1 Hz and 500 Hz from the AWG. The output amplitude is fixed throughout. The response is flat up to about 100 Hz, but then the measured amplitude drops. Note the horizontal axis is logarithmic. Bottom: Calculated impedance of the measurement circuit as a function of frequency. This shows that the amplitude drop-off as observed is not caused by impedance mismatch, since in the regime of greatest impedance change (1-100 Hz) the amplitude response is flat, while the reverse happens for higher frequencies (¿100 Hz).

The 6 csv files containing input magnetic field vs. measured magnetic field for 3 axes of the 2 sensors are available on Plone, under EDM/Magnetometers/Quspin Magnetometers/QZFM/QZFM Linearity.

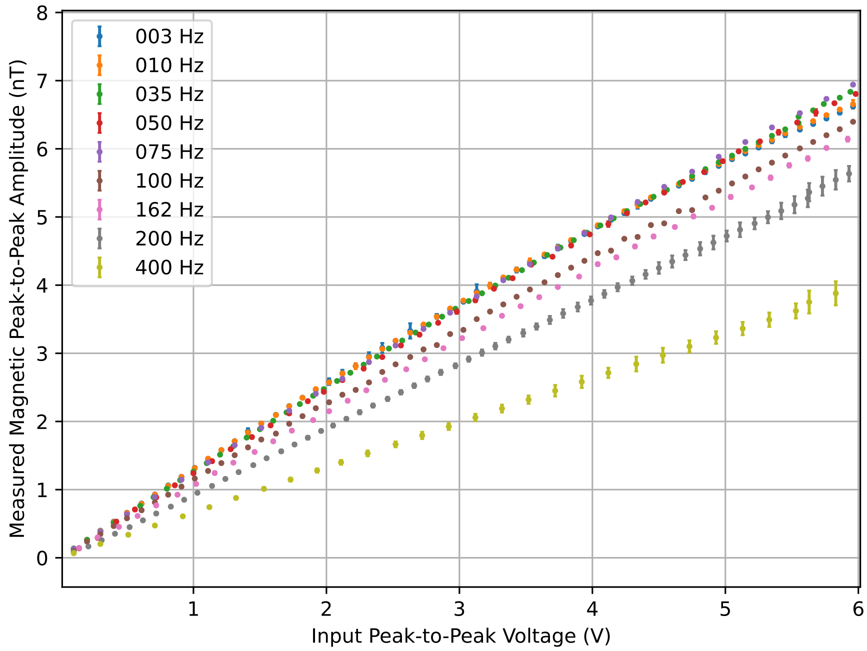

Figure 8: For the same coil/direction the frequency is varied. For frequencies below 100 Hz, the response stays constant but above this the measured amplitude steadily decreases with frequency.

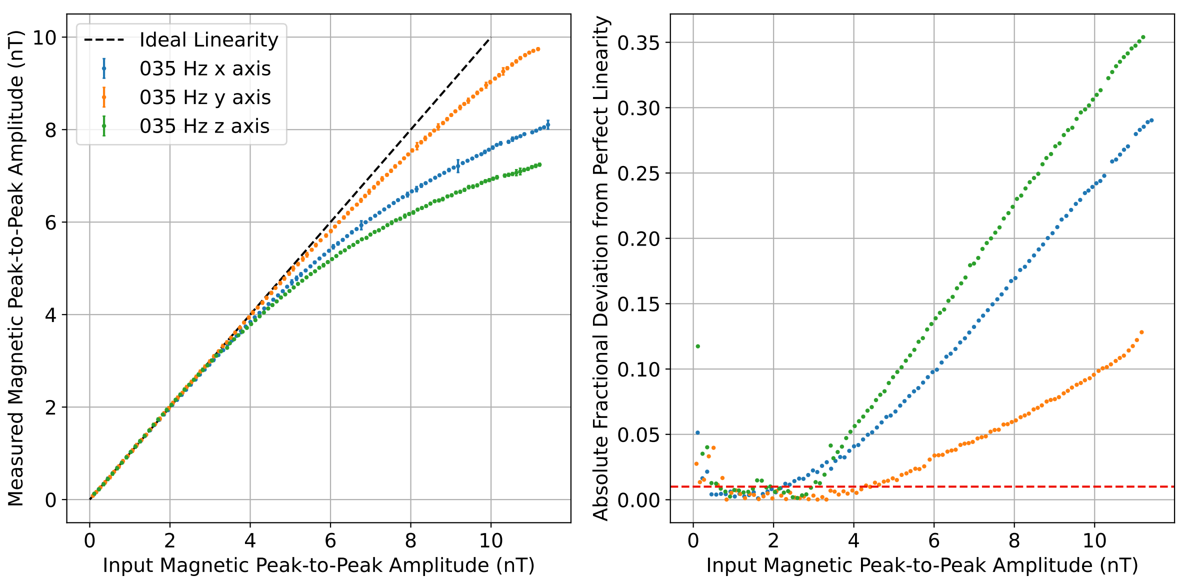

Figure 9: Results for sensor AAY4.