Quantum Design

SQUID VSM Application Note 1500-015

Accuracy of the Reported Moment: Sample Shape Effects

Abstract

The signal induced in the gradiometer of a sample magnetometer must be converted into an estimated magnetic dipole moment (in emu or A-m^2) in order to be useful. The conversion constant represents the coupling between the sample and the detection coils and is dependent on the sample geometry (shape and size). Quantum Design's DC magnetometers, including the SQUID VSM, are calibrated against the cylindrical palladium standard sample. This application note quantifies the expected magnetometer calibration errors for samples of various geometries and also validates these calculated values against measurements of a thin nickel foil. It is found that using a larger vibration amplitude will minimize this calibration error. A valuable test for inaccurately reported moments is to measure the moment at various vibration amplitudes: if the moment depends on amplitude then sample geometry effects need to be considered.

Introduction

The SQUID gradiometer measures the number of magnetic flux lines penetrating the plane of the detection coils. Some of the flux lines of a small sample with a moment of, say, m = 1.0 emu will close inside the coils, thus not being detected because there is zero net flux. However, if a sample of 1.0 emu moment completely fills the detection coils then none of these lines will close within the coils and will all be detected. This means that the coils will report different moments for these two samples although they actually have the same moment. In fact, a flat sample like a thin film will have a reported moment which depends strongly on orientation and this example is discussed below. Another important effect is the dependence of reported moment on the vibration amplitude. The instrument is calibrated to report the same magnetic moment for the cylindrical palladium standard at all amplitudes (see Table 1). However, a sample with a different geometry will produce a different dependence of magnetic flux vs. position and the lock-in electronics will interpret this as a different moment. Consider the extreme case of a cylindrical sample that is the same diameter as the Pd standard but much taller than the detection coil separation. Since the magnetic field gradients are mostly present at the top and bottom of the sample ("magnetic charges" in the language of magnetostatics), there will be little induced signal in the coils unless the ends of the sample come close to one of the coils. This means that the moment will be most strongly underreported at small amplitudes. See samples with L=10 in Table 1. This effect is common to all inductive magnetometers, but this application note will discuss this artifact in the context of the SQUID VSM magnetometer.

Simulation results

This section describes the results of numerical simulations of measurements. For more information on the details of the modeling, please contact apps@qdusa.com . The following tables show the calculated reported moment for a 1.0 emu sample for several cylindrical geometries where L is the vertical length (along the axis of the gradiometer) and D is the diameter (examples: $L = D = 0$ is a point dipole; $L = 0$, $D = 3$ is a flat disk; $L = 3$, $D = 0$ is a vertical wire). A result of less than 1.0 in this table thus indicates that the moment will be underreported. We will hereafter refer to this quantity in the tables and graphs as the *moment artifact* with the understanding that this is the multiplicative factor by which the moment is misreported. All these tables assume that the system is fully calibrated using a standard Pd sample, that the sample is fully and homogeneously magnetized, and they do not account for any sample demagnetization effects. The demagnetization effect is important in samples where both the ratio L/D is small and the sample differential magnetic susceptibility $\chi(H) = dM/dH$ is high. For a more detailed discussion of demagnetizing fields correction factors, see Sec. 2.9 in “Introduction to Magnetic Materials” by B. D. Cullity and C. D. Graham, IEEE Press (2009). Note that an amplitude dependent correction function has been applied in both tables such that the reported moment for the Pd sample is accurate.

Sample Size (mm)		Vibration Amplitude (mm)								
L	**D**	**0.5**	**1.0**	**2.0**	**3.0**	**4.0**	**5.0**	**6.0**	**7.0**	**8.0**
0	0	1.072	1.071	1.067	1.061	1.055	1.050	1.046	1.042	1.039
0	1	1.078	1.077	1.072	1.066	1.060	1.054	1.050	1.046	1.042
0	2	1.096	1.095	1.089	1.081	1.073	1.067	1.061	1.056	1.052
0	3	1.128	1.125	1.118	1.108	1.097	1.088	1.080	1.074	1.068
0	4	1.175	1.171	1.161	1.146	1.131	1.118	1.108	1.100	1.092
0	5	1.239	1.235	1.219	1.198	1.176	1.159	1.145	1.134	1.123
0	6	1.326	1.320	1.296	1.265	1.234	1.209	1.190	1.176	1.161
1	0	1.064	1.063	1.060	1.055	1.049	1.045	1.041	1.038	1.035
1	1	1.070	1.069	1.065	1.059	1.054	1.049	1.045	1.041	1.038
1	2	1.087	1.086	1.081	1.074	1.067	1.060	1.055	1.051	1.047
1	3	1.116	1.115	1.108	1.098	1.089	1.080	1.074	1.068	1.063
1	4	1.160	1.158	1.148	1.135	1.121	1.109	1.100	1.092	1.085
1	5	1.220	1.216	1.202	1.183	1.164	1.147	1.135	1.124	1.114
1	6	1.302	1.296	1.274	1.246	1.218	1.195	1.178	1.164	1.151
2	0	1.042	1.041	1.038	1.035	1.032	1.029	1.026	1.024	1.022
2	1	1.047	1.046	1.043	1.040	1.036	1.032	1.030	1.027	1.025
2	2	1.064	1.062	1.059	1.054	1.049	1.044	1.041	1.038	1.034
2	3	1.092	1.091	1.085	1.078	1.071	1.064	1.059	1.055	1.050
2	4	1.134	1.132	1.124	1.114	1.103	1.093	1.086	1.079	1.073
2	5	1.192	1.189	1.177	1.162	1.145	1.131	1.120	1.111	1.102
2	6	1.270	1.265	1.247	1.223	1.200	1.179	1.164	1.151	1.139
3	0	1.002	1.001	1.001	1.000	1.000	1.000	0.999	0.999	0.999
3	1	1.007	1.006	1.006	1.005	1.004	1.003	1.003	1.003	1.002
3	2	1.022	1.022	1.020	1.019	1.017	1.015	1.014	1.013	1.012
3	3	1.049	1.048	1.045	1.042	1.038	1.035	1.032	1.030	1.027
3	4	1.088	1.087	1.082	1.076	1.069	1.063	1.058	1.054	1.050
3	5	1.141	1.139	1.132	1.121	1.111	1.101	1.093	1.086	1.079
3	6	1.211	1.208	1.196	1.180	1.163	1.148	1.136	1.126	1.115
3.8	2.8	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
5	0	0.893	0.894	0.898	0.904	0.910	0.916	0.922	0.928	0.934
5	1	0.897	0.898	0.902	0.907	0.914	0.920	0.925	0.931	0.936
5	2	0.909	0.910	0.914	0.919	0.925	0.930	0.935	0.940	0.945
5	3	0.929	0.930	0.933	0.938	0.943	0.948	0.952	0.955	0.959
5	4	0.959	0.959	0.962	0.966	0.970	0.973	0.975	0.977	0.979
5	5	0.998	0.998	1.000	1.003	1.005	1.006	1.006	1.006	1.006
5	6	1.048	1.048	1.049	1.050	1.049	1.048	1.045	1.042	1.039
10	0	0.540	0.542	0.551	0.564	0.581	0.601	0.622	0.646	0.672
10	1	0.541	0.544	0.552	0.566	0.583	0.602	0.624	0.647	0.673
10	2	0.546	0.548	0.557	0.571	0.588	0.608	0.629	0.653	0.679
10	3	0.554	0.557	0.566	0.579	0.597	0.617	0.638	0.662	0.687
10	4	0.566	0.568	0.577	0.592	0.609	0.630	0.651	0.675	0.700
10	5	0.580	0.583	0.592	0.607	0.626	0.647	0.668	0.691	0.716
10	6	0.598	0.601	0.611	0.627	0.646	0.668	0.690	0.712	0.736

Table 1: Moment artifact for a sample of various cylindrical geometries and at various peak vibration amplitudes. The grey highlighted row is the geometry of the Pd standard sample against which the instrument is calibrated.

Sample Size (mm)		Vibration Amplitude (mm)								
L	**Orientation**	**0.5**	**1.0**	**2.0**	**3.0**	**4.0**	**5.0**	**6.0**	**7.0**	**8.0**
1	horizontal	1.079	1.078	1.073	1.067	1.061	1.055	1.050	1.047	1.043
2	horizontal	1.103	1.101	1.095	1.087	1.079	1.071	1.065	1.060	1.055
2.38	horizontal	1.117	1.116	1.109	1.099	1.089	1.081	1.074	1.069	1.063
3	horizontal	1.150	1.148	1.139	1.126	1.114	1.103	1.094	1.087	1.080
4	horizontal	1.217	1.213	1.199	1.180	1.161	1.145	1.132	1.122	1.112
5	horizontal	1.313	1.307	1.284	1.254	1.225	1.201	1.183	1.168	1.155
1	vertical	1.068	1.067	1.063	1.057	1.052	1.047	1.043	1.040	1.037
2	vertical	1.056	1.055	1.051	1.047	1.043	1.039	1.035	1.033	1.030
2.38	vertical	1.048	1.048	1.045	1.041	1.037	1.034	1.031	1.028	1.026
3	vertical	1.034	1.034	1.032	1.029	1.026	1.024	1.022	1.020	1.019
4	vertical	1.004	1.004	1.004	1.004	1.004	1.004	1.003	1.003	1.003
5	vertical	0.964	0.965	0.967	0.971	0.974	0.977	0.979	0.981	0.983

Table 2: Moment artifact for a square film sample of various sizes and oriented with the magnetometer axis along the plane of the film (“vertical”) or perpendicular to the plane of the film (“horizontal”).

Note that, as a general trend, samples with similar vertical and transverse dimensions (L=D in Table 1 and “vertical” orientation in Table 2) will have more accurately reported moments. That is because these samples will look similar to a point source dipole to the gradiometer.

In order to better visualize the results, Figure 1 shows data for a few geometries out of the table (two square films in either orientation, a flat thin round disk, and a long thin wire).

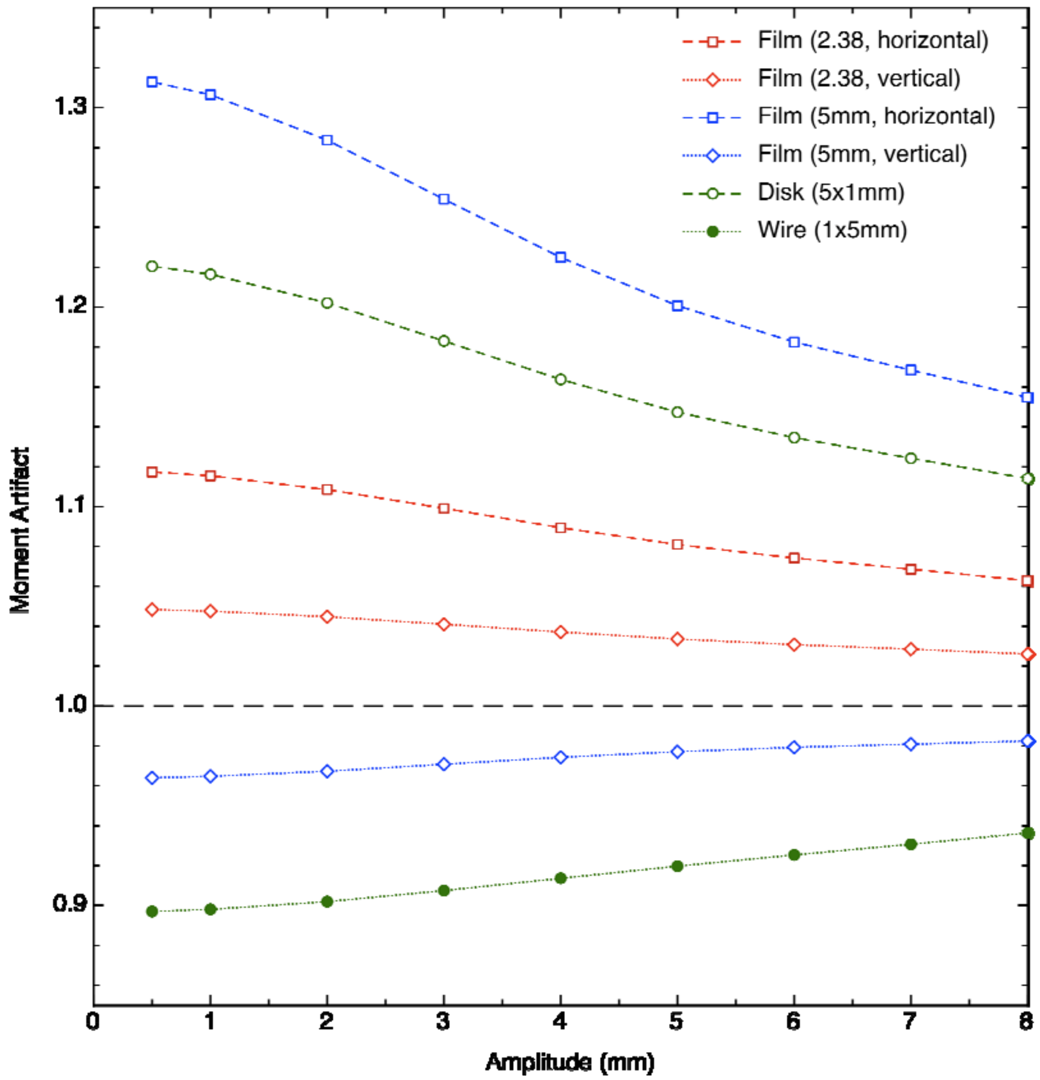

Figure 1: Moment artifact for some selected sample geometries listed in Tables 1 and 2.

As is clearly visible from the plot, larger vibration amplitudes will report the real moment more faithfully. Therefore, the general guideline in SQUID VSM measurements is to use the largest vibration amplitude possible in order to get best accuracy as well as precision. The exception to this guideline is when a large amplitude produces temperature or SQUID instabilities, an effect sometimes seen at low temperatures. However, as this is a purely geometric effect, the amplitude dependence for a given sample can be determined at room temperature (where using large amplitudes should not cause any issues), allowing to correct the reported moment data at other temperatures after the fact. Although the shape of the curves looks similar, it has been found that they cannot be collapsed successfully onto one universal curve by normalizing them to the moment artifact at, say, 0.5mm.

Comparing simulations with measurements

The above calculated results were validated by measuring a square nickel film (2.38 x 2.38 x 0.025mm^3), see photograph in Figure 2 of sample mounted on a 3.5mm diameter glass rod in preparation for a measurement in the horizontal orientation. All measurements were performed in a field large enough to make sure that the sample was fully saturated (i.e., the sample differential susceptibility was small) so that demagnetization effects could be neglected.

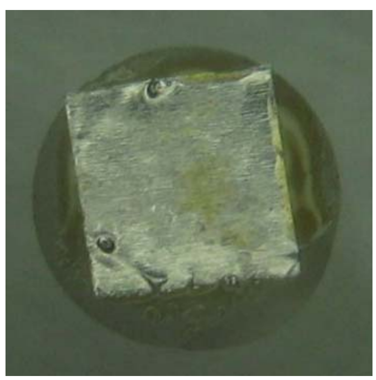

Figure 2: Photograph of nickel foil sample mounted to a glass rod and adhered with a small amount of vacuum grease.

Figure 3 shows a comparison between the measured and simulated amplitude dependence for both orientations (top graph) as well as the measured and calculated ratio of the reported moment between the two orientations (bottom graph). Simulation data was scaled to best fit the measured data.

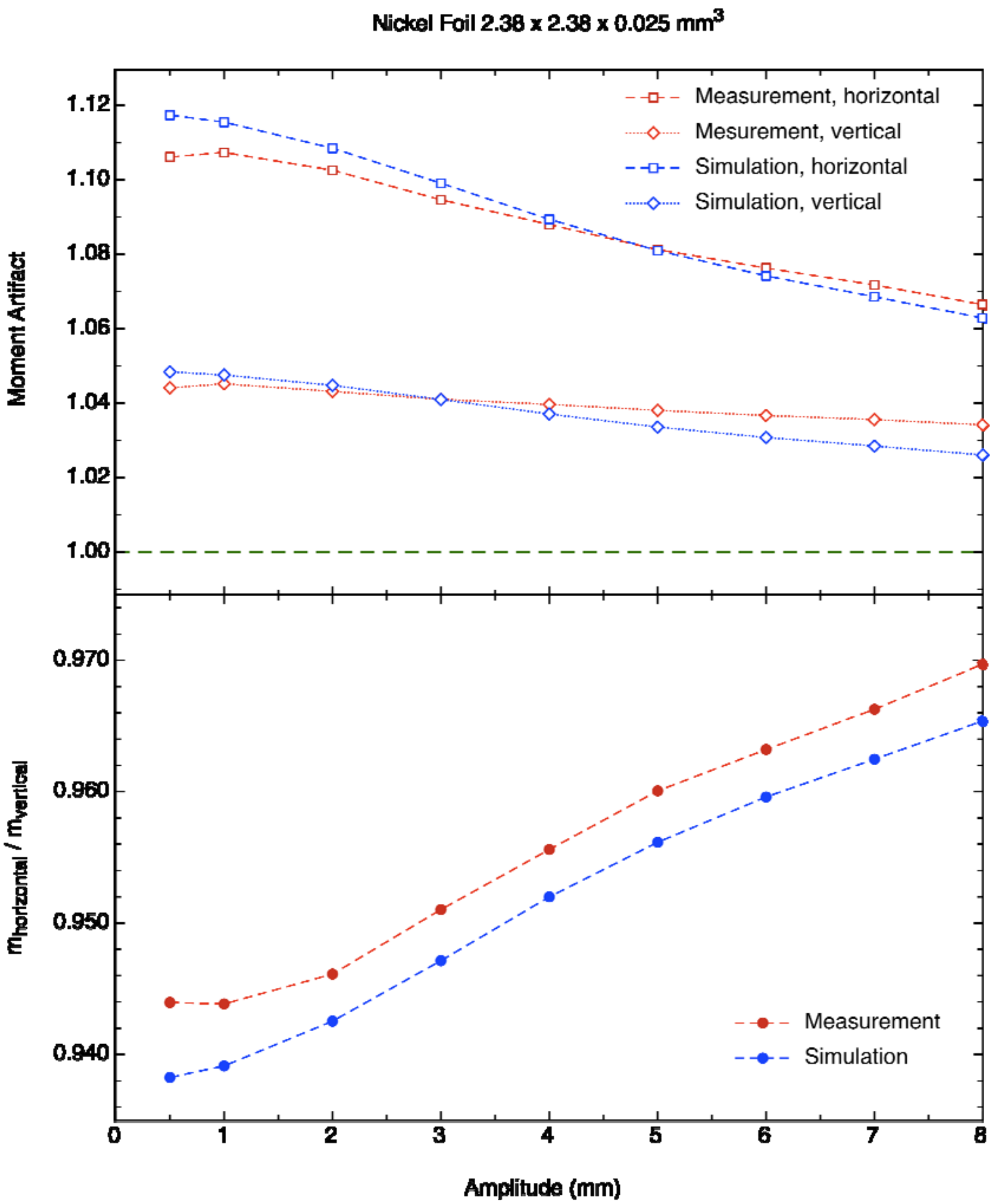

Figure 3: Comparison between the measured and simulated amplitude dependence for a thin square nickel film.

The agreement between the simulation and the measurement, although not perfect, is reasonable considering other factors such as axial and radial sample centering which also affect the reported moment accuracy (see SQUID VSM application note 1500-010 for more on this topic).

Conclusions

Significant systematic error in the reported moment in the SQUID VSM can result in samples whose geometry differs from the palladium standard sample. These effects are intrinsic to any induction magnetometer in which the detection coils are put close to the sample. The following guidelines will help to mitigate these effects:

1) choose a large vibration amplitude (5mm or higher)
2) choose a sample geometry that is tabulated in Table 1 or Table 2
3) samples whose transverse dimension (width of film or diameter of cylinder) is similar to sample length (along magnetometer axis) will present less moment artifact
4) measure the sample at various vibration amplitudes: if there is a dependence of reported moment on the amplitude then sample geometry effects need to be considered when reporting the moment of the sample