Contents

1 Introduction

With help of a SQUID we measure the magnetic field of a current loop with five different currents and of everyday items like a crown cork. We are able to rotate the samples so we can have a look on the magnetic field in polar form. In addition to that we calculate the theoretical magnetic field of the loops and the one we will measure with the SQUID. With knowledge about the magnetic field we will calculate the dipole moment of the current loops and the samples. For the different resistances we can compare the measured values with the theoretical ones.

2 Physical background

2.1 Superconductivity

Materials which can be superconductivity are called superconductors. The characteristic behavior is that they do not have an electric resistance if you cool them down under a critically temperature T_c. In addition to that they are perfect diamagnets. A magnetic field through one generate an induced current which compensate the field B_int inside the diamagnet. This is called the Meissner-Ochsenfeld effect.
If a material is in its superconducting state there exists a temperature-dependent bandgap

$$E_\mathrm{gap} = E_\mathrm{F} \pm \Delta E. \tag{1}$$

where E_F : Fermi energy
ΔE: temperature-dependent energy

Contrary to the expectation its not needed that superconductors are metals or have crystal structures there are also polymer and organic ones. However you separate two different kinds of superconductors:

- Type 1: Superconductors with $T_\mathrm{C} < 23{,}2\,\mathrm{K}$
  If the outer magnet field is weaker than a critical field H_c it holds $B_\mathrm{int} = 0\,\mathrm{T}$. With the exception of the edge. There still exists a magnetic field till the London penetration depth (see subsection 2.3)
- Type 2: High temperature superconductors
  It is now possible that there is a magnetic field inside the conductor. There are two different critical field strengths H_C1 and H_C2. In case of H_C2 there still exists a magnetic field B_int for H_C1 there is none. If you have a field strength $H_\mathrm{C1} < H < H_\mathrm{C2}$ it comes to Abrikosov vortexes. They are areas where the material is a normal conductor and inside the areas there exists a magnetic field. All other areas are still superconductivity

2.2 Perturbation of superconductivity

There are different influences which are able to disturb the superconductivity. Here we only want to enumerate them.

- Temperature: above the critical temperature T_C the superconductor is only a normal conductor and has an electrical resistance.
- Magnetic field: a too strong magnetic field can be responsible for a recess of superconductivity

- Electric field: for the same reason an electric field can be, because it produces a magnetic field
- Alternating magneto electric field ($\omega \approx \frac{\Delta E}{\hbar}$): electrons can be excited above the bandgap. As a consequence the conductor is no longer superconductivity.

2.3 London equations

Like mentioned above one can calculate the penetration depth of the magnetic field into the superconductor. One uses the hypothesis that the acceleration is only depending on the electric field, the definition of current density j and the Maxwell equations

$$\begin{aligned}\nabla \times \vec{E} &= -\frac{1}{c}\frac{\partial \vec{B}}{\partial t} \\ \nabla \times \vec{B} &= \frac{4\pi}{c}\vec{j}\end{aligned} \tag{2}$$

and obtain the London equation

$$\nabla \times \vec{j} = -\frac{n_\mathrm{e} e^2}{mc}\vec{B} \tag{3}$$

and

$$\begin{aligned}\nabla^2 \vec{B} &= \frac{4\pi n_\mathrm{e} e^2}{mc^2}\vec{B} \\ \nabla^2 \vec{j} &= \frac{4\pi n_\mathrm{e} e^2}{mc^2}\vec{j}\end{aligned} \tag{4}$$

The solutions are exponentially falling and the penetration depth is

$$\Lambda = \sqrt{\frac{mc^2}{4\pi n_\mathrm{e} e^2}} \tag{5}$$

The consequence is that the magnetic field can insert in the conductor and it exist a current density which has a screening effect.

2.4 BSC theory

If you have a look on a normal conductor, free electrons are responsible for the conductivity that is different by superconductors. Cooper pairs are responsible there.
Cooper pairs, which are coupled electrons, based on the deformation of the atom lattice. The positive ions are heavier and as a consequence slower than the electrons. So behind an electron there is positive polarization. This polarization interacts with another electron over distances like a few lattice constants and attract it.
Electrons are fermions and near by $0\,\mathrm{K}$ nearly all atoms posses the Fermi energy E_F. So its likelier to find another electron with nearly the same momentum and even a small interaction leads to an electron couple. Coupled electrons are no longer fermions, the bond makes the both $s = \frac{1}{2}$ systems to one boson system. Hence it is possible that all Cooper pairs can go into the lower energetically state because of the Bose statistic. Another consequence is that there is only one wave function. The wavelength is much bigger than the distances of atomic cores. This is the reason why superconductors are superconductivity.

2.5 Flux quantization

The SQUID is a ring, so it holds

$$0 = \oint \vec{j} d\vec{l}. \tag{6}$$

Otherwise there would be a voltage drop and that is not possible because of superconductivity. Since we have a clearly wave function it is only possible to obtain a phase difference of $n \cdot \pi$. Also we can calculate the magnetic flux through the SQUID with help of the Stokes' theorem.

$$0 = \oint \vec{A} d\vec{l} = \Phi_{\mathrm{B}} \qquad \text{and} \qquad \oint \nabla\Theta d\vec{l} = \Delta\Theta = 2\pi n \tag{7}$$

The London equations say

$$\oint \nabla\Theta d\vec{l} = \frac{q}{\hbar} \oint \vec{A} d\vec{l} \tag{8}$$

Therefore the flux is quantized:

$$\Phi_{\mathrm{B}} = \frac{h}{q} \cdot n \qquad n \in \mathbb{Z} \tag{9}$$

2.6 Josephson effect

The Josephson effect (named after B. D. Josephson) is about the tunneling of Cooper pairs through a thin isolation layer from one superconductor to another. To understand the effect we will have a look on a simple circuit (see Figure 1). It consist of an isolation

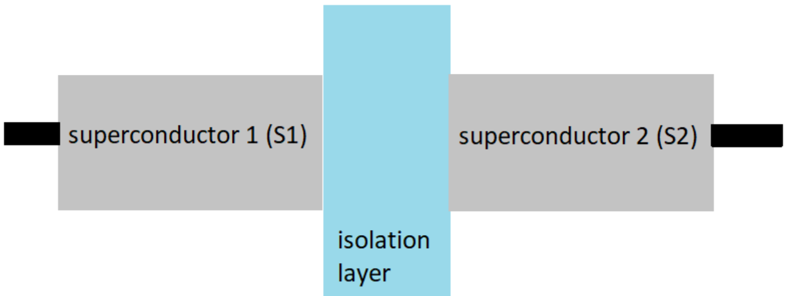


Figure 1: Isolator surrounded by two identical superconductors (Josephson contact)[4]

layer (thinner than 30 Å), which is surrounded by two identical superconductors (S1, S2); this composition is called Josephson contact. Equivalent to a single electron a Cooper pair can, because of the wave function, tunnel through the potential barrier. So the Cooper pairs don't lose energy by tunneling through the barrier, although the barrier isn't a superconductor. So a magnetic field can be in the isolation layer and change the coupling and the phase shift. The result is the so called Josephson direct current

$$I = I_0 \cdot \frac{\sin\left(\pi\Phi/\Phi_0\right)}{\pi\Phi/\Phi_0}, \tag{10}$$

while Φ is the magnetic flux and Φ_0 the flux quantum. There is also an Josephson alternating current, but it isn't relevant for this experiment.

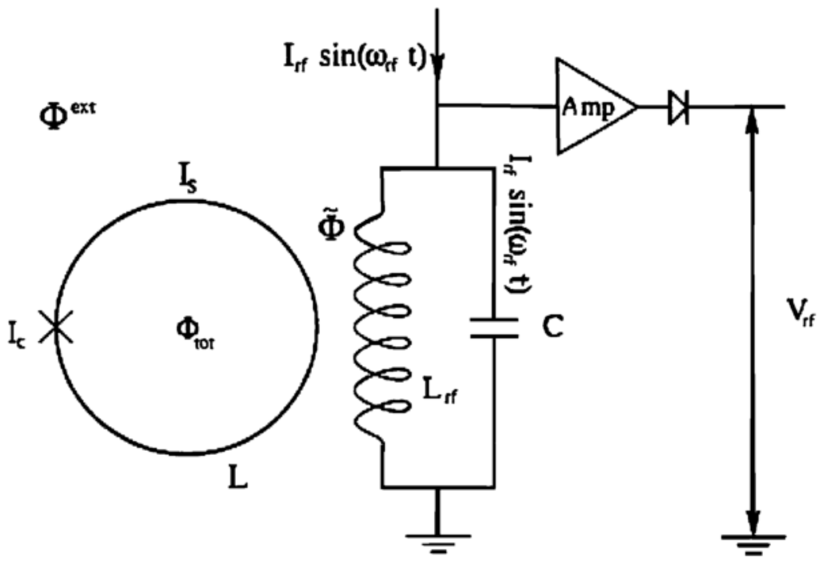


Figure 2: Sketch of a RF-Squid [2]

2.7 The SQUID

In this experiment a rf-Squid is used. It is consist of a superconductivity ring which has a Josephson contact and an oscillating circuit with an inductor which creates a magnetic field. The amplified voltage can be read out (cf. Figure 2).

The oscillation circuit with the inductor induce a current inside the superconductor. This current compensates exactly the magnetic flux Φ_{tot} inside. The external field can not achieve a change of the intern flux if it is smaller than a flux quantum Φ_0. For holding the flux still stable there is a screening current near the surface. This current creates a flux

$$\Phi_{\text{S}} \tag{11}$$

and so we obtain

$$\Phi_{\text{tot}} = \Phi_{\text{ext}} - LI_{\text{S}}. \tag{12}$$

The number of flux quanta only change if the screening current exceeds the critical one. Then the ring is no longer superconductivity and it can now start with another number of flux quanta.
Because of the Josephson contact is is a quit complicated behavior, with the phase difference

$$\Theta_2 - \Theta_1 = 2\pi n - 2\pi \frac{\phi_{\text{tot}}}{\Phi_0} \tag{13}$$

and with $I_{\text{S}} = I_{\text{S,max}} \sin{(\Theta_2 - \Theta_1)}$ we obtain

$$\Phi_{\text{tot}} + LI_{\text{S,max}} \sin{(\frac{2\pi\Phi_{\text{tot}}}{\Phi_0})}. \tag{14}$$

During the experiment we measure the voltage applied to the circuit. Every time the current reaches the critical one the superconductor becomes a normal conductor and need energy for holding the screening current. This energy comes out of the circuit and we can measure the damping by measuring the voltage.

2.8 LockIn method

We want to mention the LockIn method only in passing. A LockIn amplifier is used if it is needed to detect a weak signal over a heavy noise. The amplifier modulates the measured signal with a high frequency signal. The LockIn detector demodulates it later on. With this technique it is possible to archive a better signal.

2.9 Calculating the magnetic field

You can calculate the magnetic field of a current loop with

$$B_\mathrm{z} = \frac{\mu_0}{2\pi}\frac{p}{z^3} \qquad \text{with} \quad p = AI = A\frac{AV}{R}, \tag{15}$$

where p : dipole moment,
z : distance between sample and measurement point.

To obtain the magnetic field with the data of the SQUID you have to convert the voltage $\Delta\, V$ to a flux. For calculating the magnetic field we have to know the area of the aperture of the SQUID. Because of the superconductivity only a small part gets inside the ring. However you can use the field flux coefficient $F = 9,3[\frac{nT}{\Phi_0}]$. Then it holds

$$B_\mathrm{z} = F\frac{\Delta V}{k}. \tag{16}$$

3 Setup and implementation

3.1 Setup

The whole setup is shown in Figure 3. The main part is the Dewar. It is filled with

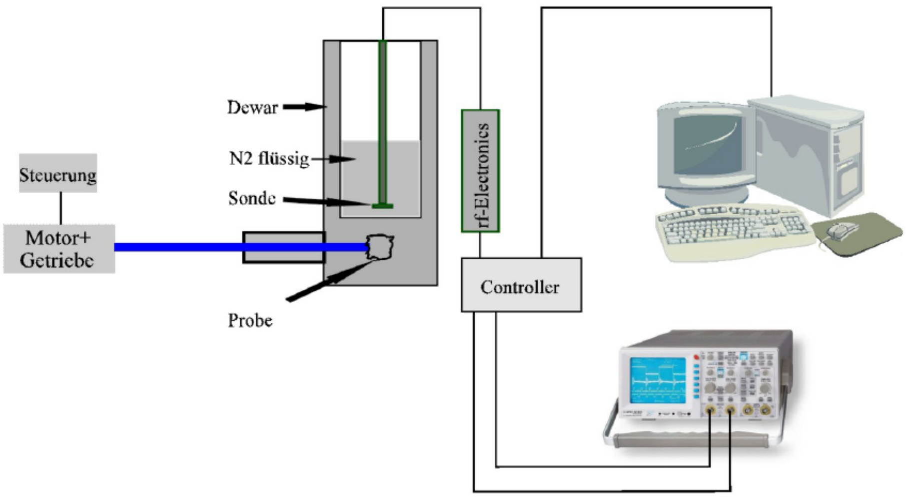


Figure 3: Setup [2]

liquid nitrogen for cooling down the SQUID which is also inside the dewar. The sample is separated below the space for the nitrogen. It can be twisted with held of a motor. The Signal of the SQUID goes to electronic boxes and then to a PC and an oscilloscope. The data can be read out with the program "HMlab" and "JSQ Duo Sensor Control".

3.2 Implementation

First step is to fill the dewar with liquid nitrogen. After that you have to put the SQUID inside the dewar and wait about 15 min to be sure that the conductor is cold enough to be superconductivity. After that one can start the PC programs "HMLab" and "JSQ Duo Sensor" and set the settings to test. We obtain the typical SQUID pattern which should be optimized by changing the settings of "VCA", "VCO" and "OFF". If the optimal values are found one can go to measure mode.
You start with a conductor loop and place it below the SQUID. The signal of the loop is to be measured with different rotating velocities and different resistances which regulate the current inside the loop.
Next step is to measure everyday items like coins, magnetic chips or a little metal stab.
In addition to that it is important to measure the distance between the SQUID and the samples and to notice the settings of the PC program.

4 Analysis

4.1 Distances

To get the distance z between the SQUID and the conductor loop respectively the sample, we measured the distance between dewar lid and sample $b = (30{,}7 \pm 0{,}2)\,\mathrm{cm}$ and the distance between dewar lid and SQUID $c = (26{,}5 \pm 0{,}3)\,\mathrm{cm}$ and calculate the difference

$$\begin{aligned} z &= b - c = 4{,}2\,\mathrm{cm}, \\ s_\mathrm{z} &= \sqrt{s_\mathrm{b}^2 + s_\mathrm{c}^2} = 0{,}4\,\mathrm{cm}. \end{aligned} \tag{17}$$

Also important for the future calculation is the radius of the conductor loop. We only measured the diameter $d_\mathrm{loop} = (3{,}5 \pm 0{,}5)\,\mathrm{mm}$, so we get for the radius

$$r = \frac{d}{2} = (1{,}8 \pm 0{,}3)\,\mathrm{mm}. \tag{18}$$

4.2 Theoretical magnetic fields of the conductor loops

For calculating the magnetic field of a conductor loop we can use formula 15.
Needed values are the the voltage $U = (2{,}610 \pm 0{,}013)\,\mathrm{V}$ applied on the resistance, the resistance R itself, the radius r of the conductor loop and the distance z between the loop and the SQUID.
The uncertainty has its origin in the voltmeter. We used METEX M3800 with the uncertainties $\pm 0,5\% \pm 1\,\mathrm{digit}$. The resistances and their uncertainties are given in the manual. The values are shown in Table 1.

Resistance	R [Ω]	s_R [Ω]
1	51,47	0,05
2	100,8	0,10
3	300,8	0,3
4	510,6	0,5
5	1000,0	1,0

Table 1: Used resistances

With the values above we are able to calculate the magnetic field

$$B = \frac{\mu_0}{2} \cdot \frac{Ur^2}{R \cdot z^3} \tag{19}$$

and its uncertainty

$$s_\mathrm{B} = B \cdot \sqrt{\left(\frac{s_U}{U}\right)^2 + \left(2 \cdot \frac{s_\mathrm{r}}{r}\right)^2 + \left(\frac{s_R}{R}\right)^2 + \left(3 \cdot \frac{s_\mathrm{z}}{z}^2\right)}.$$

With this calculus we obtain the following values shown in Table 2.

Resistance	B[nT]
1	$1{,}3 \pm 0{,}5$
2	$0{,}7 \pm 0{,}3$
3	$0{,}23 \pm 0{,}09$
4	$0{,}13 \pm 0{,}05$
5	$0{,}07 \pm 0{,}03$

Table 2: Magnetic fields of the different current loops

4.3 Measured magnetic fields of the conductor loops

We measured for the different resistances and several rotational speeds the voltage with the SQUID. The conversion from the setup of the motor to the rotational frequency is denoted in Table 3.

Setting w	Rotational frequency [mHz]
1	25
2	50
5	125
10	250

Table 3: Motor settings and the related rotational frequencies

On the oscilloscope was for each time a vertical line, which describes the value and it's uncertainty. The output were two values, the highest and the lowest value of the line. We decided to plot both values in the diagrams, because Origin[1] uses for the fit automatically the mean. The gotten values were each plotted in graphic (voltage over time) and a sine function of the form

$$U(t) = A + B\sin(C \cdot t + D) \tag{20}$$

was fitted (with Origin[1]) on them. The graphics are in the appendix (figures 4 ff.).
The noise of resistance R5 by motor setting of $w = 2$ (50 mHz) was very high compared to the actual signal, so a sine fit wasn't possible as you can see in figure 26. Therefore it doesn't exist a computation for this setting.

To calculate the magnetic field we use B from the Fit-Parameters, the field flux coefficient $F = 9{,}3\,\frac{\mathrm{nT}}{\Phi_0}$, which is given from the manufacturer, and the value of the feedback resistor

$$R = 100\,\mathrm{k\Omega} \quad \Rightarrow \quad k = 1{,}900\,\frac{\mathrm{V}}{\Phi_0}. \tag{21}$$

The formula to calculate the magnetic field B_z is then

$$\begin{aligned} B_\mathrm{z} &= F \cdot \frac{B}{k}, \\ s_{B_\mathrm{z}} &= F \cdot \frac{s_\mathrm{B}}{k}. \end{aligned} \tag{22}$$

The calculated values of the different resistances are summed up in Table 4.

Resistance	w	B [V]	s_B [V]	B_z [nT]	s_{B_z} [nT]
R1	1	0,3776	0,0013	1,848	0,006
R1	2	0,3620	0,0014	1,772	0,007
R1	5	0,3668	0,0013	1,795	0,006
R1	10	0,3575	0,0013	1,750	0,006
R2	2	0,1960	0,0009	0,959	0,004
R2	5	0,1891	0,0008	0,926	0,004
R2	10	0,2071	0,0008	1,014	0,004
R3	2	0,0614	0,0012	0,301	0,006
R3	5	0,0705	0,0009	0,345	0,004
R3	10	0,0699	0,0009	0,342	0,004
R4	2	0,0456	0,0011	0,223	0,005
R4	5	0,0380	0,0010	0,186	0,005
R4	10	0,0407	0,0010	0,199	0,005
R5	5	0,0227	0,0009	0,111	0,004
R5	10	0,0233	0,0009	0,114	0,004

Table 4: Magnetic fields of the different resistances by several motor settings

To get a final result for each resistance we calculate the arithmetic mean

$$\begin{aligned} \overline{x} &= \frac{1}{N} \cdot (x_1 + x_2 + \ldots + x_N), \\ s_{\overline{x}} &= \frac{1}{N} \cdot \sqrt{s_{x_1}^2 + s_{x_2}^2 + \ldots + s_{x_N}^2}. \end{aligned} \tag{23}$$

So we get the results which are summed up in Table 5.

Resistance	B_z [pT]
R1	1791 ± 3
R2	966 ± 2
R3	329 ± 3
R4	203 ± 3
R5	113 ± 3

Table 5: Magnetic fields of the different resistances

4.4 Measured magnetic fields of the samples

In addition to the resistance it were also several samples (crown cork, metal stick, magnetic flake, 2€ coin, empty aluminum holding). The proceed to get the magnetic fields of the samples is equivalent to the proceed of the resistances, so it is not listed again (see 4.3). A difference is that the used feedback-resistor was in two cases different, it was

$$\text{crown cork, magnetic flake, empty aluminum holding: } R = 100\,\mathrm{k\Omega} \Rightarrow k = 1{,}900\,\frac{\mathrm{V}}{\Phi_0},$$

$$\text{magnetic stick, 2€ coin: } R = 1\,\mathrm{k\Omega} \Rightarrow k = 0{,}021\,\frac{\mathrm{V}}{\Phi_0}.$$

For the crown cork a sinusoidal run isn't visible (cf. Figure 26), so it isn't possible to calculate a magnetic field. The others are shown in figures 26,27, 29, 31, 33 and additional a sine function is fitted with Origin[1]. To calculate the effective magnetic field, we made also an underground measurement with the empty aluminum holding. But the value is so small that it can be neglected. The results of the magnetic field are written in Table 6.

Sample	B_z [nT]
empty aluminum holding	$0{,}029 \pm 0{,}015$
magnetic flake	$27{,}08 \pm 0{,}09$
metal stick	1952 ± 5
2€ coin	1687 ± 13

Table 6: Magnetic fields of the different samples

4.5 Polar form of the magnetic fields

To get the polar form of the force of the magnetic field in dependence of the rotation angle are more computations necessary. First we need the parameters A, C and D from the sine fit. For a measured voltage U_i the related effective magnetic field is

$$B_{\mathrm{z,i}} = F \cdot \frac{U_\mathrm{i} - A}{k}. \tag{24}$$

Because the graphics are just visualizations and are not necessary for following calculations, we leave the error calculation out. On the polar form graphics is

$$y_\mathrm{i} = |B_{\mathrm{z,i}}| \cdot \sin(C \cdot t + D) \tag{25}$$

over

$$x_\mathrm{i} = |B_{\mathrm{z,i}}| \cdot \cos(C \cdot t + D) \tag{26}$$

plotted with Origin[1]. We did this for all samples, except the crown cork, because of a missing sine fit, and for the resistances exemplary for $w = 10$. The reason for the decision $w = 10$ is that here are the data the best (less change of noise). The oscilloscope gave always two values for one time step (see subsection 4.3), so we decided to make in the graphics a line from one to the other. The polar form graphics of the resistances are visible in Figure 5, 10, 14, 18 and 22, the polar form graphics of the samples in Figure 28, 30, 32 and 34.

4.6 Dipole moments of current loops and samples

At first we want to calculate the theoretical dipole moment p_t and its uncertainty s_{p_t} with following formula

$$\begin{aligned} p_\mathrm{t} &= I \cdot A = \pi r^2 \frac{U}{R} \\ s_{p_\mathrm{t}} &= \vec{p} \cdot \sqrt{\left(\frac{2 \cdot s_\mathrm{r}}{r}\right)^2 + \left(\frac{s_\mathrm{U}}{U}\right)^2 + \left(\frac{s_\mathrm{R}}{R}\right)^2}. \end{aligned} \tag{27}$$

For the calculating the dipole moment p_m and its uncertainty $s_{p_\mathrm{m}}$with the measured values of the SQUID we use formula 15:

$$\begin{aligned} p_\mathrm{m} &= \frac{2\pi z^3}{\mu_0} B_\mathrm{z} \\ s_{p_\mathrm{m}} &= p_\mathrm{m} \cdot \sqrt{\left(\frac{3 \cdot s_\mathrm{z}}{z}\right)^2 + \left(\frac{s_{\mathrm{B_z}}}{B_\mathrm{z}}\right)}. \end{aligned}$$

The calculated values are shown in Table 7.

resistance	p_{t} [$\mathrm{nA} \cdot \mathrm{m}^2$]	p_{m} [$\mathrm{nA} \cdot \mathrm{m}^2$]
1	490 ± 140	660 ± 170
2	250 ± 70	360 ± 90
3	80 ± 20	120 ± 30
4	49 ± 14	75 ± 19
5	25 ± 7	42 ± 10

Table 7: Dipole moments of the different current loops (theoretical and measured ones)

We did the same calculation with the samples. However it is obviously that we only can calculate the dipole moment via the measured values. According to the above-mentioned calculation we obtain the values shown in Table 8.

Sample	p_{m} [$\mu\mathrm{A} \cdot \mathrm{m}^2$]
magnetic flake	10 ± 3
metal stick	720 ± 190
2 €	630 ± 160
empty holder	$0{,}011 \pm 0{,}006$

Table 8: Dipole moments of the different samples

5 Conclusion

We start the discussion with a short presentation of our measured values for the resistance. You can read them out of Table 9.

Resistance	B_t[nT]	B_m[nT]
1	$1{,}3 \pm 0{,}5$	$1{,}791 \pm 0{,}003$
2	$0{,}7 \pm 0{,}3$	$0{,}966 \pm 0{,}002$
3	$0{,}23 \pm 0{,}09$	$0{,}329 \pm 0{,}003$
4	$0{,}13 \pm 0{,}05$	$0{,}203 \pm 0{,}003$
5	$0{,}07 \pm 0{,}03$	$0{,}113 \pm 0{,}003$

Table 9: Theoretical magnetic fields B_t and measured ones B_m of the different current loops

As you can see the theoretical values have a much bigger uncertainty than the measured ones. The reason of this can be find by looking at the needed distance z between loop and SQUID. It was not possible to measure the distance exactly because of the setup and the gauge. For details of calculating the uncertainties look at chapter 4.1 and 4.2. In addition to that the uncertainties of the measured magnetic fields seems to be very small. This is a little fallacy. We calculate the mean of three different measurements which were all a little bit difference from each other. The small uncertainty is a result of the computation of the error of the mean. However we can say that the different of the theoretical and the measured magnetic field is one standard deviation for the first two resistances and two standard deviations for the resistances 3-5. From resistance 1 to resistance 5 the magnetic fields decreases. We expected that because a higher resistance means a lower current and as a consequence a lower magnetic field.

We also calculated the dipole moment of the conductor loops. We obtained the values shown in Table 10.

resistance	p_t [$\mathrm{nA \cdot m^2}$]	p_m [$\mathrm{nA \cdot m^2}$]
1	490 ± 140	660 ± 170
2	250 ± 70	360 ± 90
3	80 ± 20	120 ± 30
4	49 ± 14	75 ± 19
5	25 ± 7	42 ± 10

Table 10: Theoretical dipole moments p_t and measured ones p_m of the different current loops

When we compare the results one can say that the calculated dipole moment and the measured one has a distance of 1 standard deviation if you use the uncertainty of the measured value. The others have a distance of 2 standard deviations.

We also computed the magnetic field and the dipole moments of different everyday items. The results are listed in Table 11.

Sample	B_z [nT]	p_m [$\mu A \cdot m^2$]
magnetic flake	$27{,}08 \pm 0{,}09$	10 ± 3
metal stick	1952 ± 5	720 ± 190
2 €	1687 ± 13	630 ± 160
empty holder	$0{,}029 \pm 0{,}015$	$0{,}011 \pm 0{,}006$

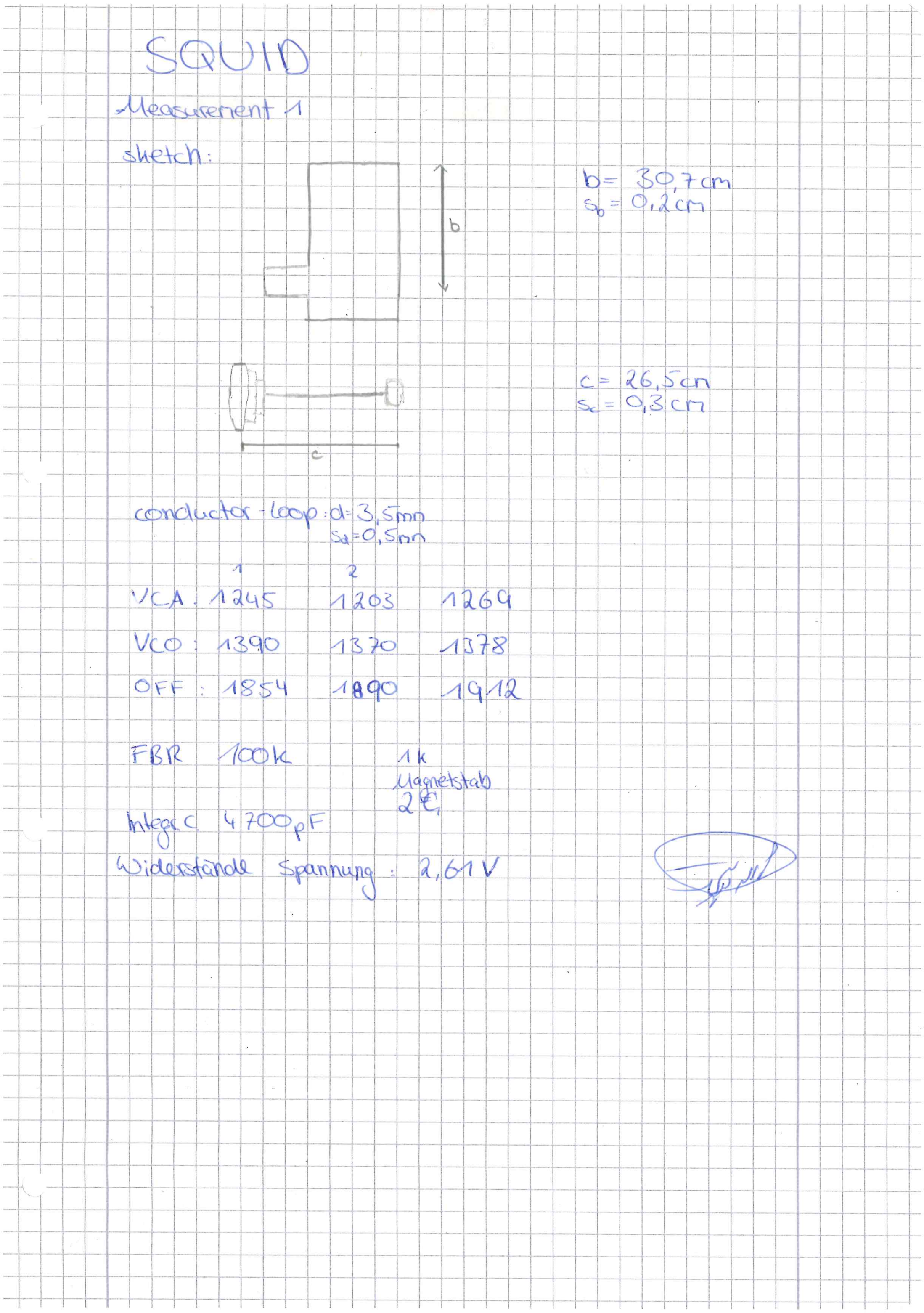
Table 11: Magnetic fields and dipole moments of the different samples

Here we can read out the smallest measurable magnetic field we could gather. It was the empty aluminum holder with the magnetic field $B = (29 \pm 15)\,\mathrm{pT}$. In theory there should be no magnetic field. The fact that we had measured a field is not bad at all because it is very small and has only a little influence on the other measurements so we decided to ignore this error.
The highest magnetic field was created by the metal stick. Here we measured $B = (1952 \pm 13)\,\mathrm{nT}$.

The polar form graphics have only a visualization function, anyway there can be got some informations from it. A perfect dipole with perfect measurements will show in such a diagram two stacked circles with the midpoint in the origin. In this case the distance of a point on the circle is the size of the magnetic field and the angle with the x-axis to the origin is the rotational angle of the resistance/sample. In our experiment we get different results. On the one hand the first three resistances (R1, R2 and R3) have a very clear pattern, on the other hand on the patterns of the resistances R4 and R5 is nearly no pattern visible. Just for y-values near by zero adumbrate the pattern. A explanation is that the uncertainty of the oscilloscope is for this resistances much higher than for the first ones. For example is the amplitude by R5 comparatively small to the distance of the two value series. The effect is visible in polar form plots. It also is to mention that all used resistances aren't perfect dipoles, because there are rather ellipses with a long semi-axis, which are parallel to the y-axis, visible.
For the samples we tested first a crown cork, but we didn't measure a periodical signal. Maybe the settings of the oscilloscope weren't really good. The plot of the empty aluminum holding is approximately a circle, so it isn't a strong dipole or the dipole moment is very weak. So the effect on the other samples is negligible. For the 2€ coin, the magnetic flake and the metal stick have all clear patterns, but the expected circles are all asymmetric. A possible explanation is that the samples were skew in the aluminum holding.

6 Appendix

6.1 Notes


SQUID

Measurement 1

sketch:

b = 30,7 cm
s_b = 0,2 cm

c = 26,5 cm
s_c = 0,3 cm

conductor-loop: d = 3,5 mm
s_d = 0,5 mm

	1	2	
VCA:	1245	1203	1269
VCO:	1390	1370	1378
OFF:	1854	1890	1912

FBR 100k 1k

Magnetstab 2€

Integr. C 4700 pF

Widerstände Spannung: 2,61 V

6.2 Diagrams current loops

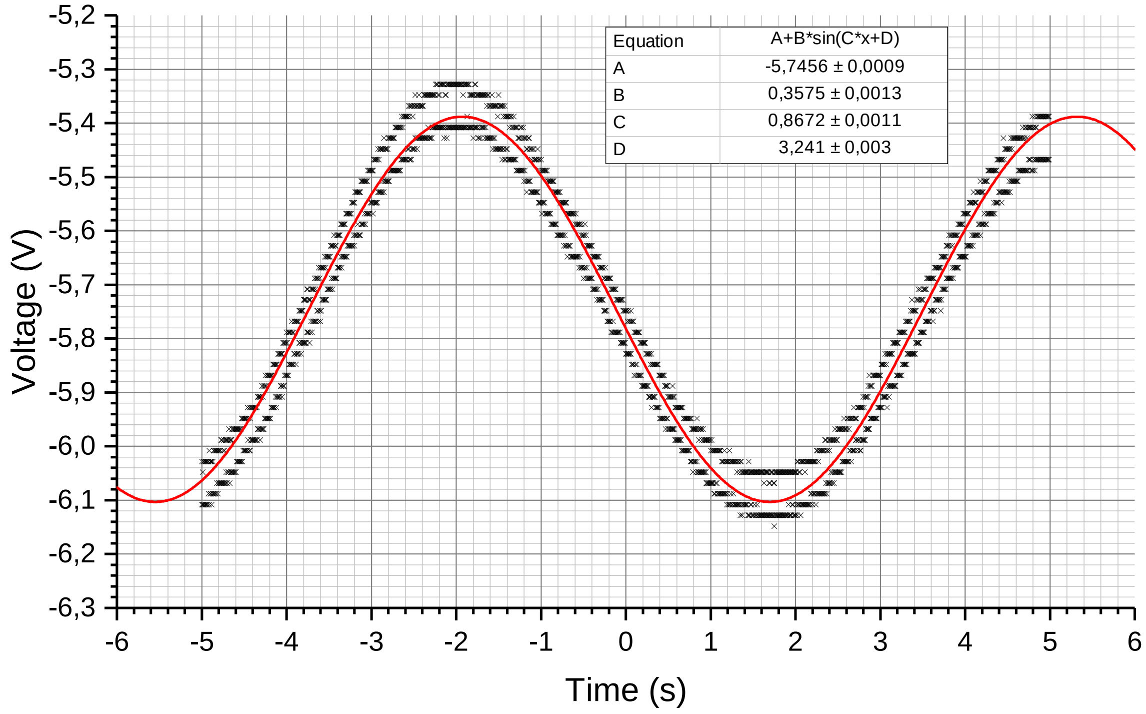


Figure 4: Resistance 1 with rotating setting $w = 10$ [1]

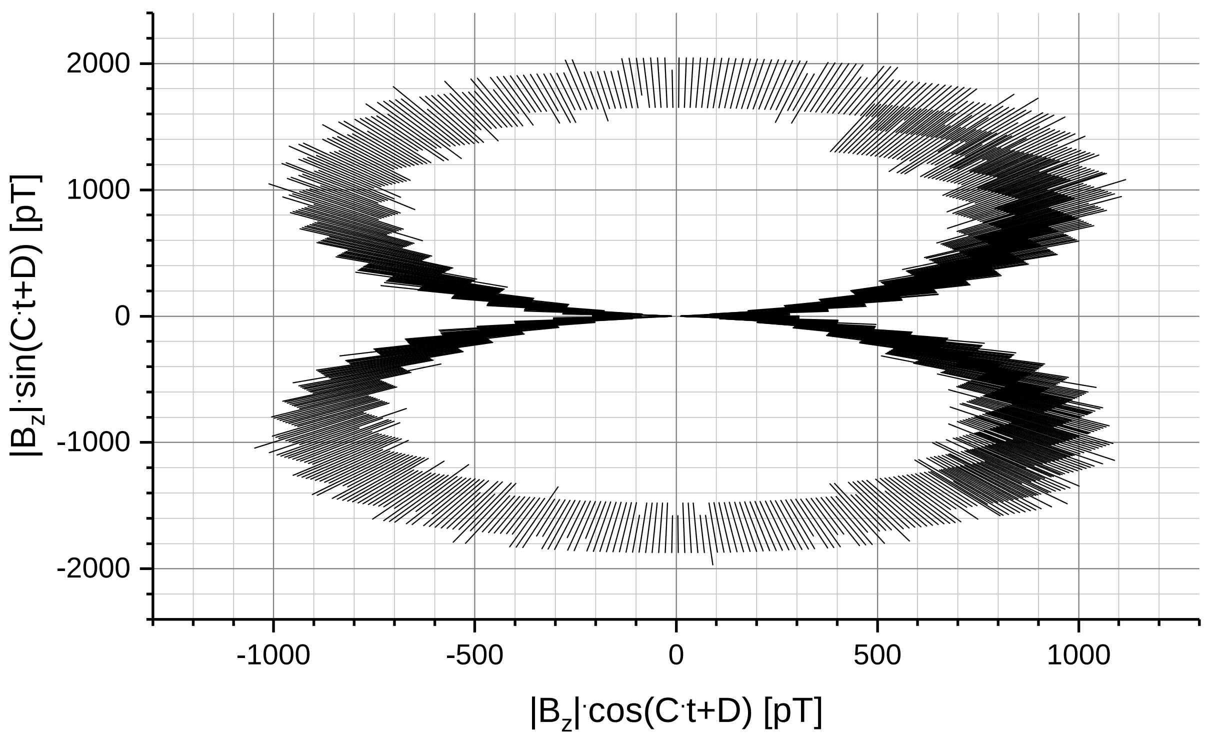


Figure 5: Resistance 1 with rotating setting $w = 10$ in polar form [1]

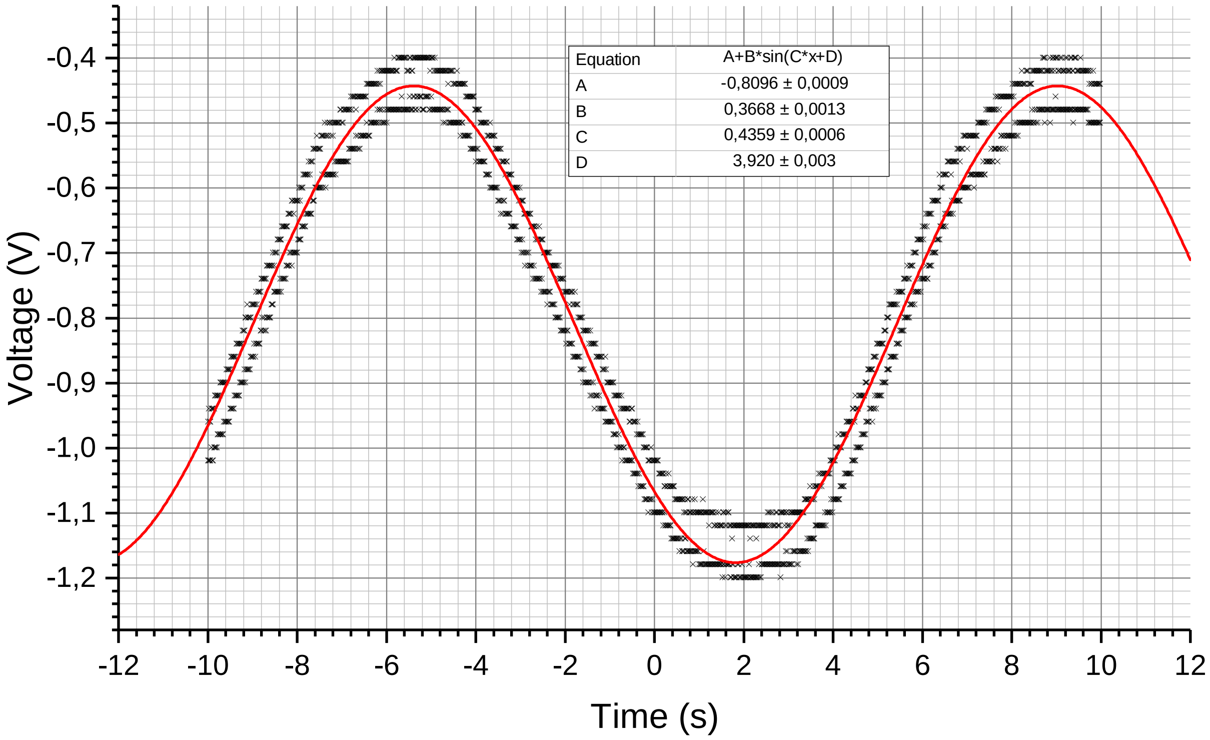


Figure 6: Resistance 1 with rotating setting $w = 5$ [1]

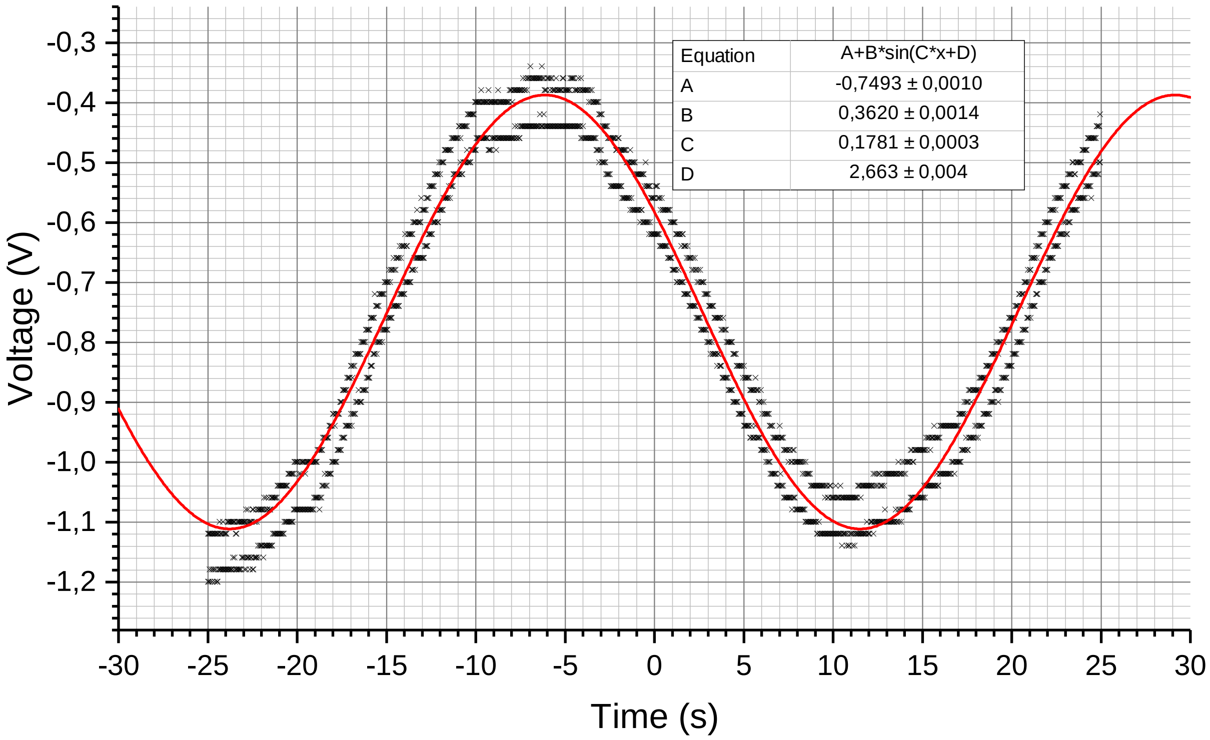


Figure 7: Resistance 1 with rotating setting $w = 2$ [1]

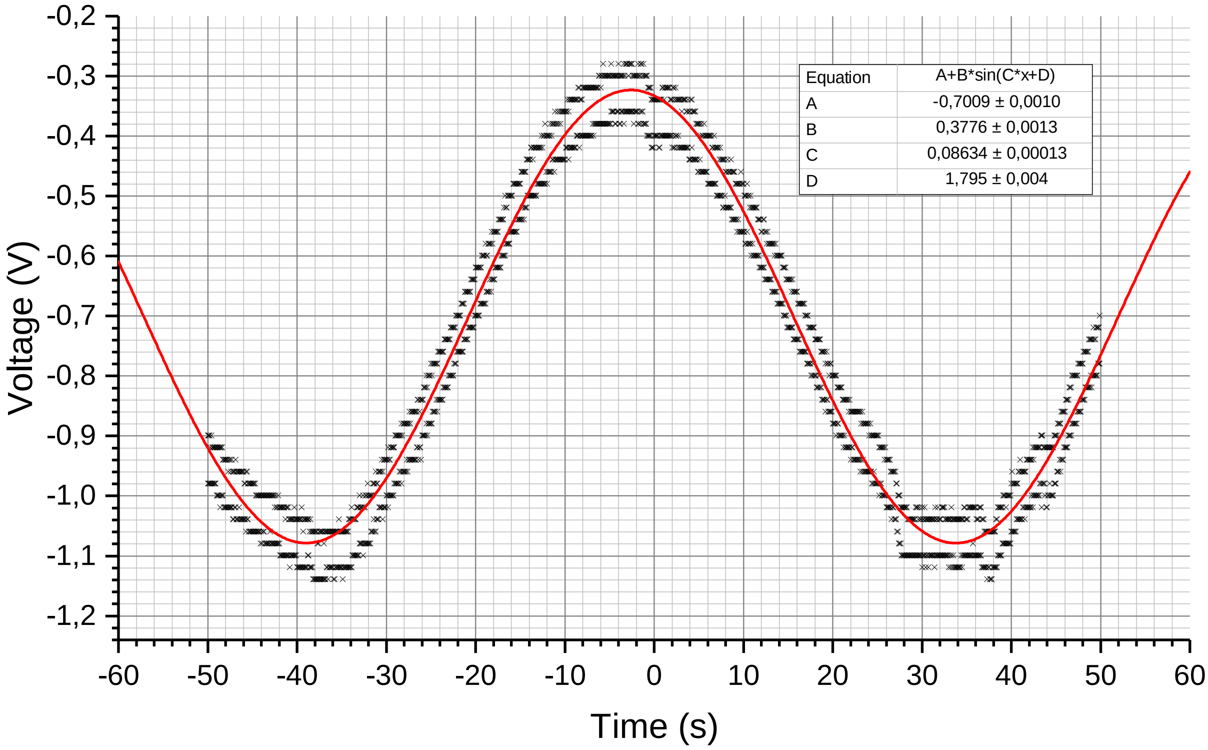


Figure 8: Resistance 1 with rotating setting $w = 1$ [1]

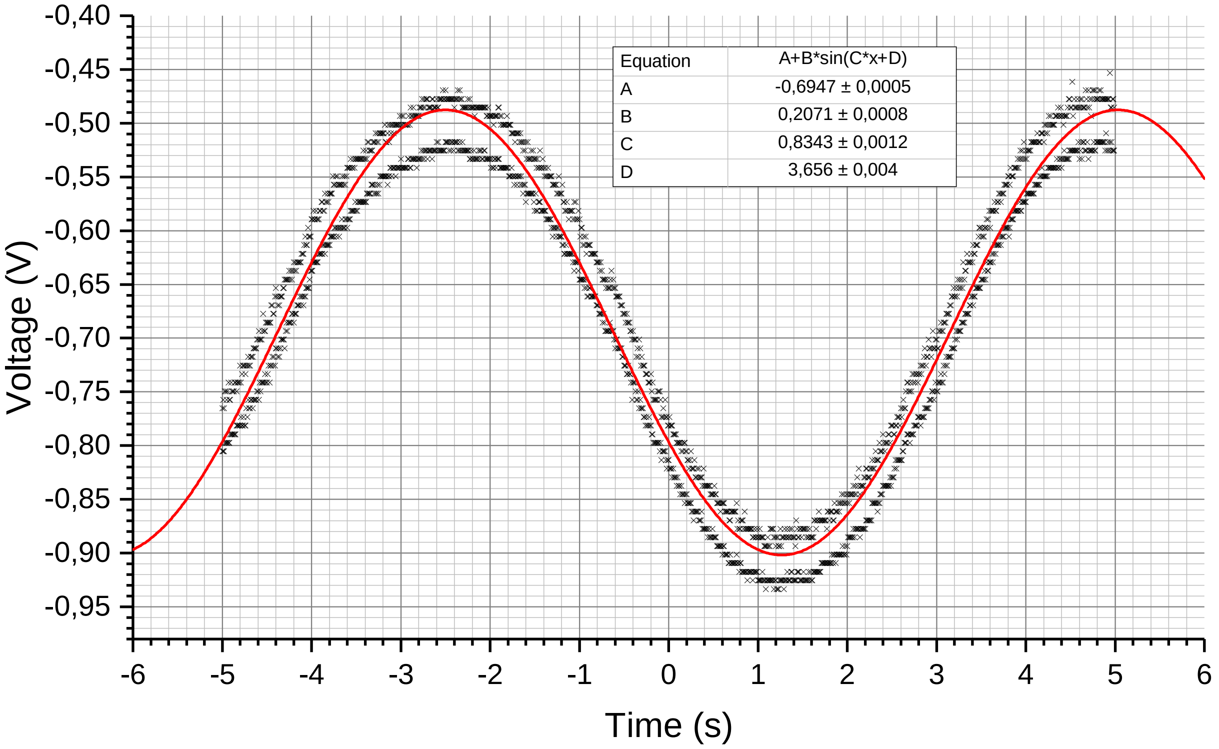


Figure 9: Resistance 2 with rotating setting $w = 10$ [1]

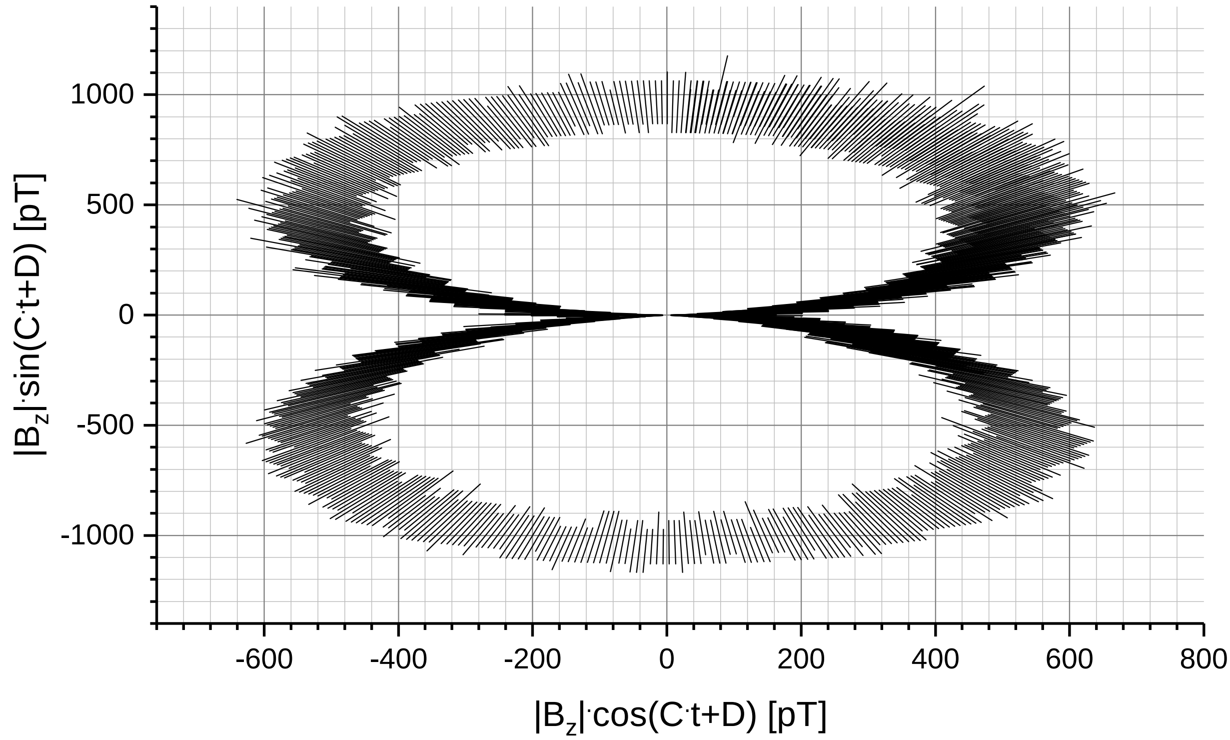


Figure 10: Resistance 2 with rotating setting $w = 10$ in polar form [1]

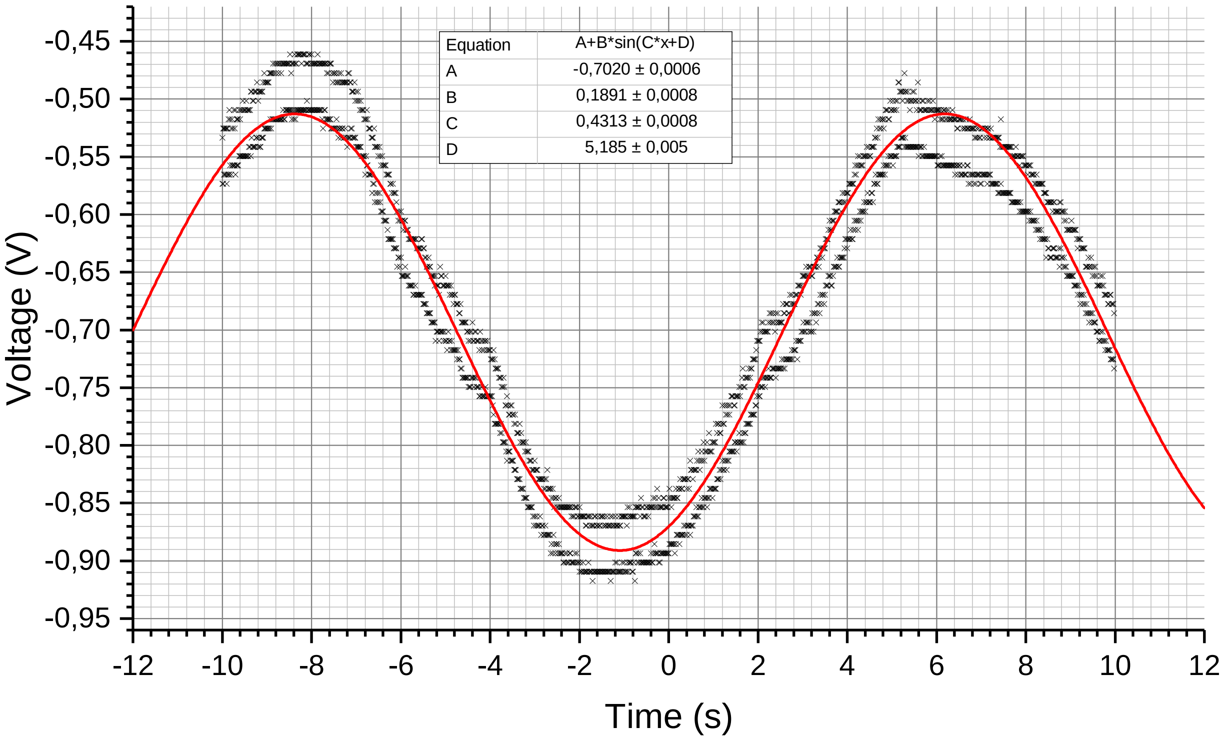


Figure 11: Resistance 2 with rotating setting $w = 5$ [1]

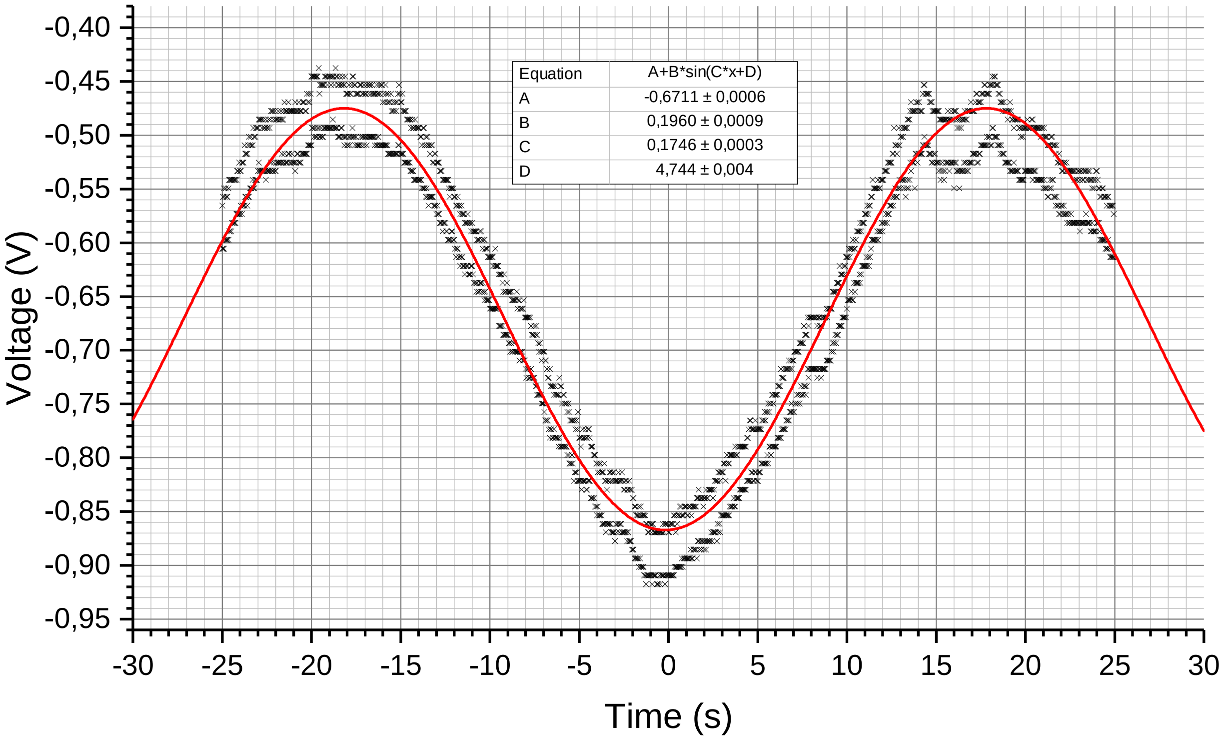


Figure 12: Resistance 2 with rotating setting $w = 2$ [1]

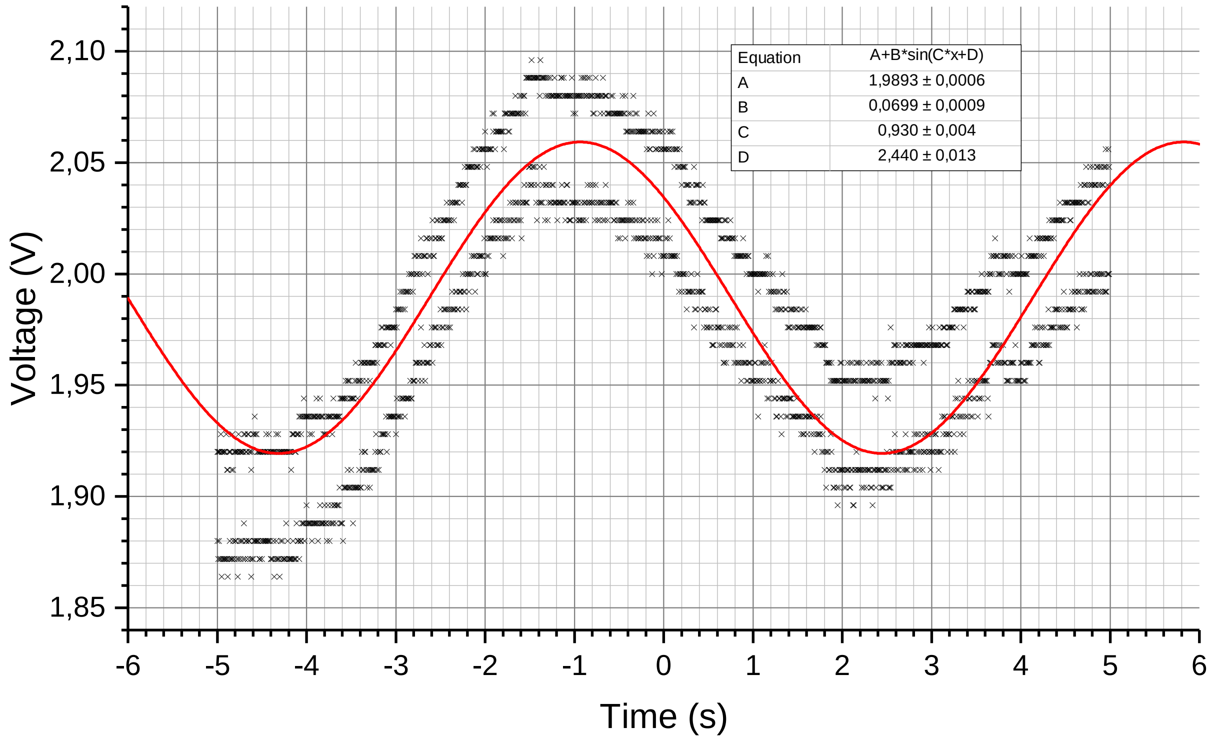


Figure 13: Resistance 3 with rotating setting $w = 10$ [1]

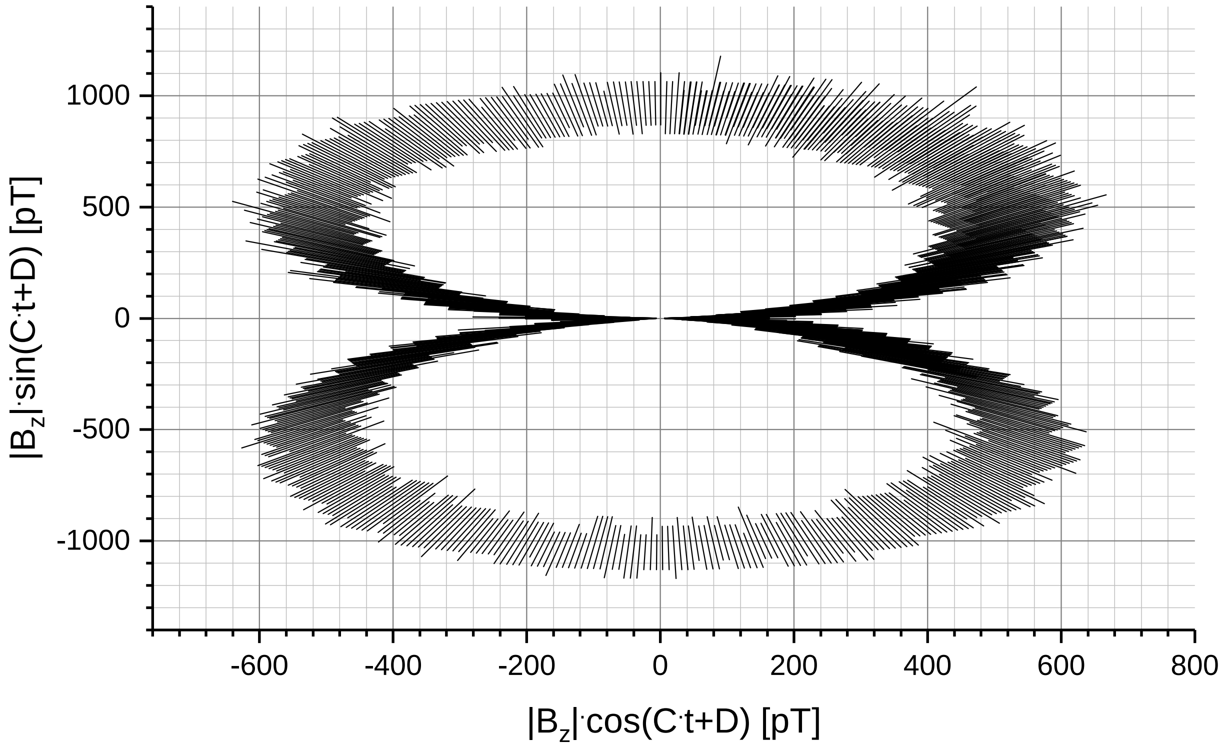
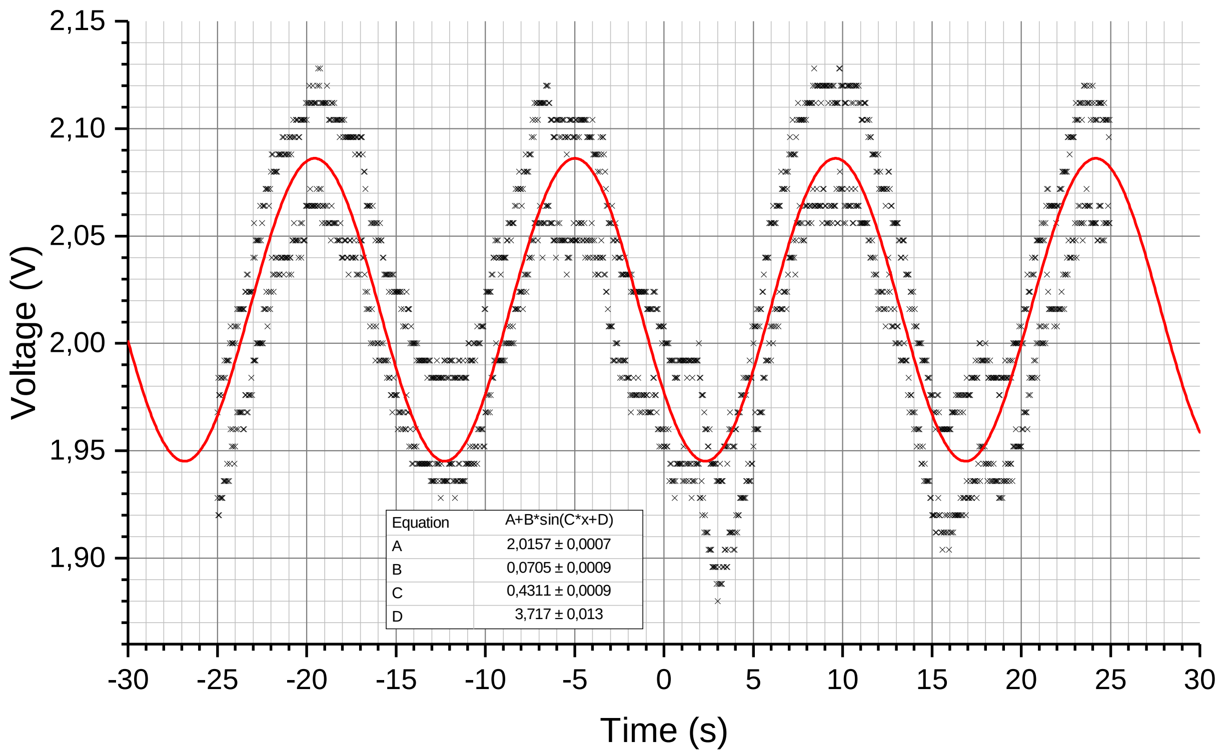


Figure 14: Resistance 3 with rotating setting $w = 10$ in polar form [1]



Equation	A+B*sin(C*x+D)
A	2,0157 ± 0,0007
B	0,0705 ± 0,0009
C	0,4311 ± 0,0009
D	3,717 ± 0,013

Figure 15: Resistance 3 with rotating setting $w = 5$ [1]

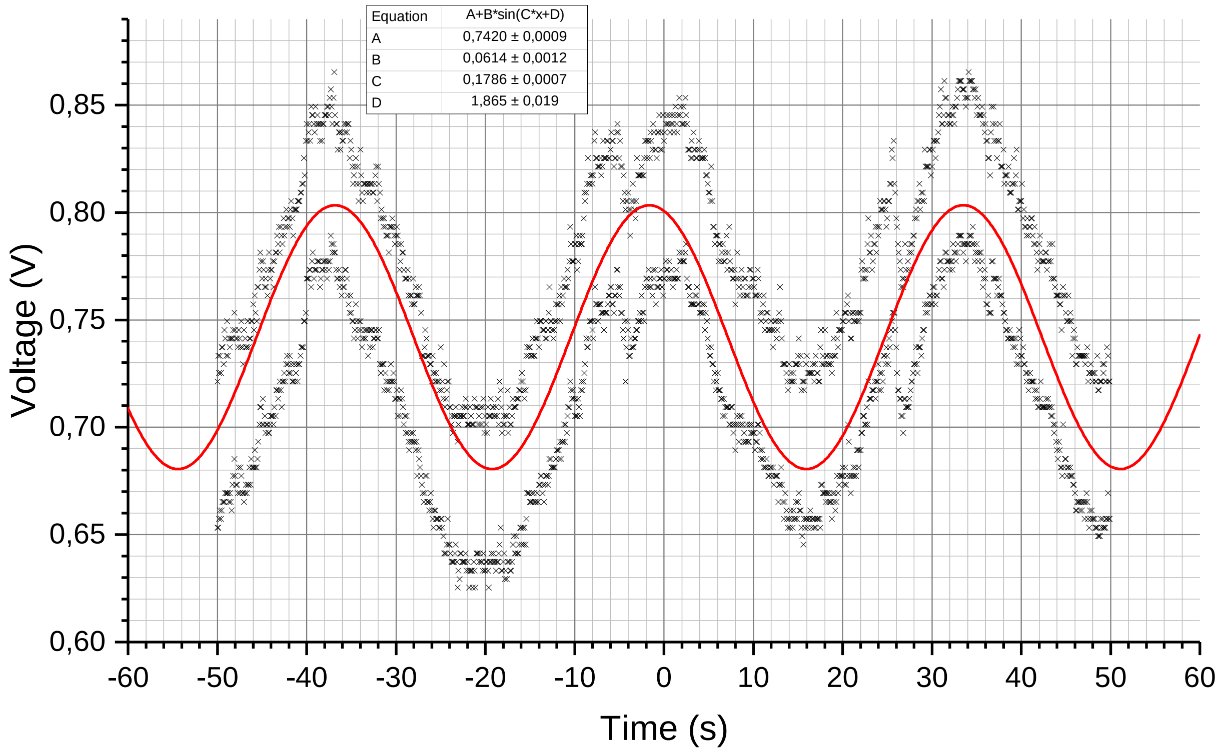


Figure 16: Resistance 3 with rotating setting $w = 2$ [1]

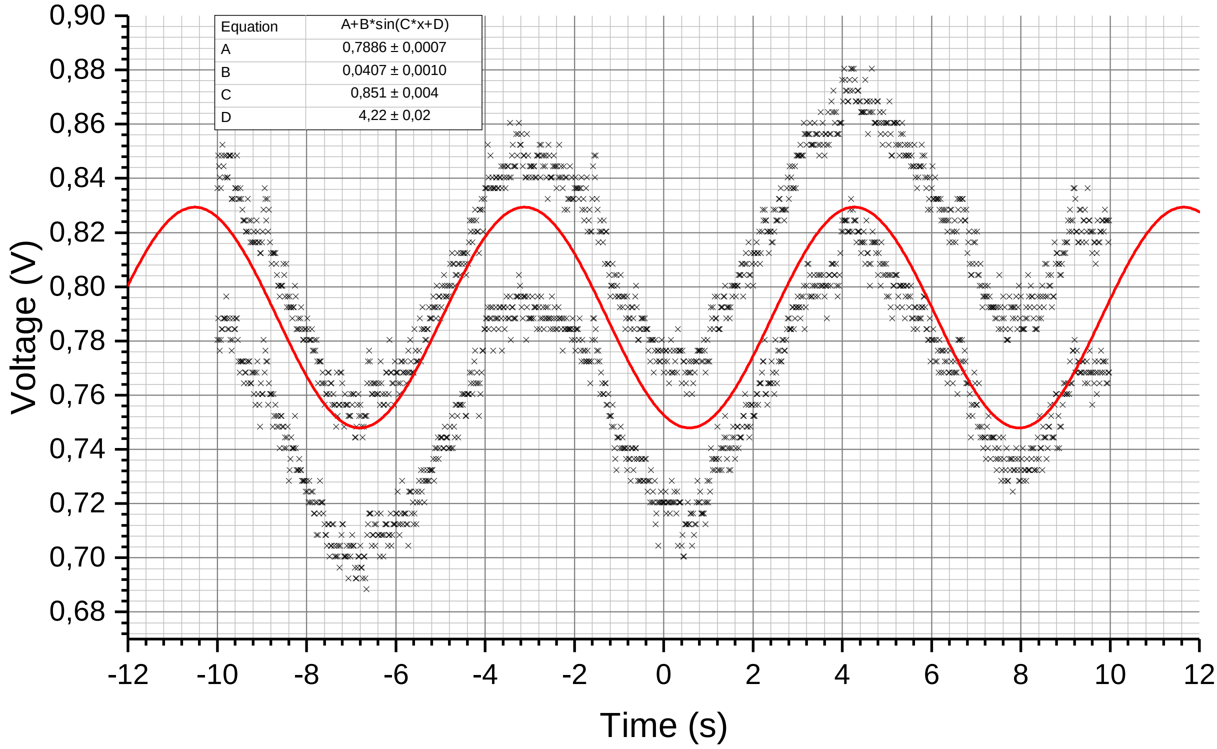


Figure 17: Resistance 4 with rotating setting $w = 10$ [1]

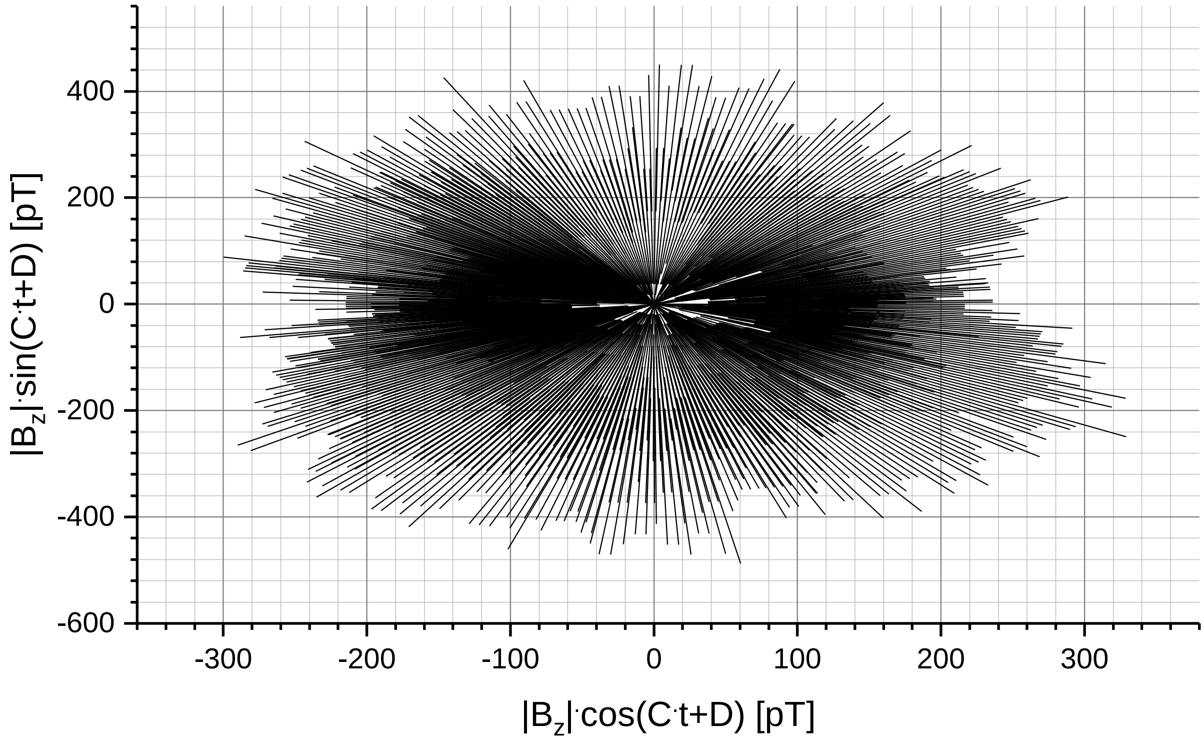


Figure 18: Resistance 4 with rotating setting $w = 10$ in polar form [1]

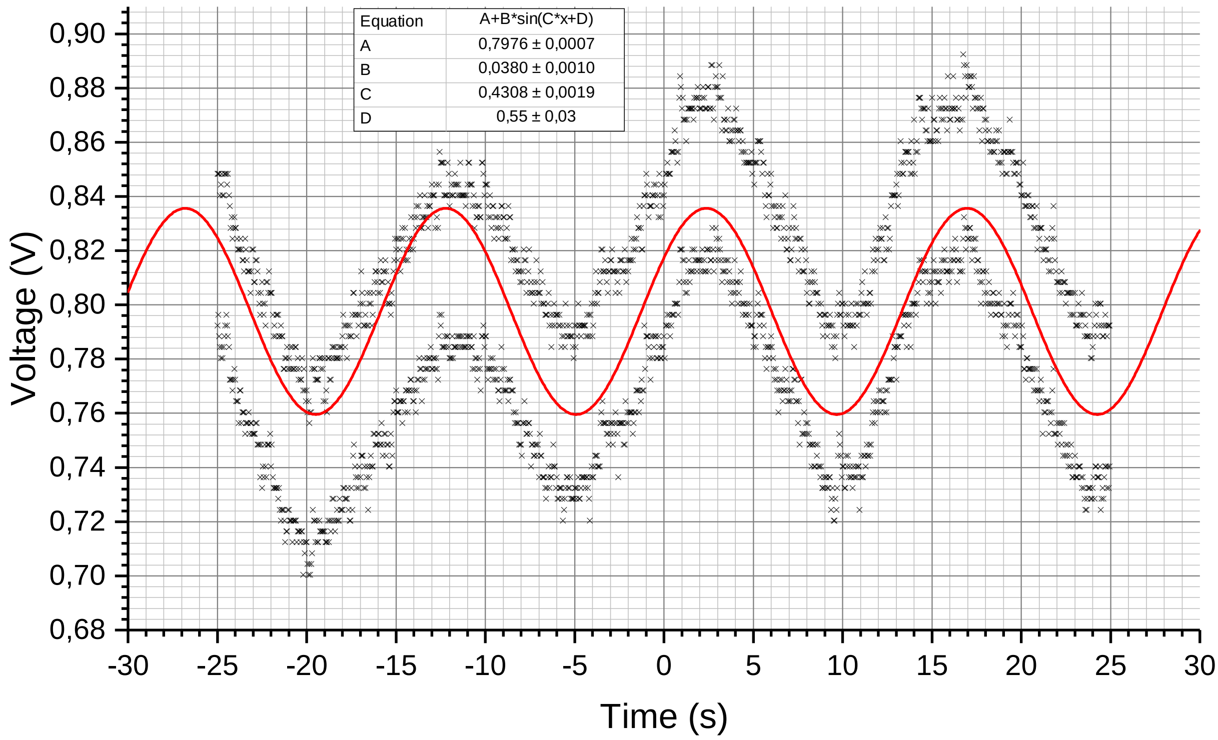


Figure 19: Resistance 4 with rotating setting $w = 5$ [1]

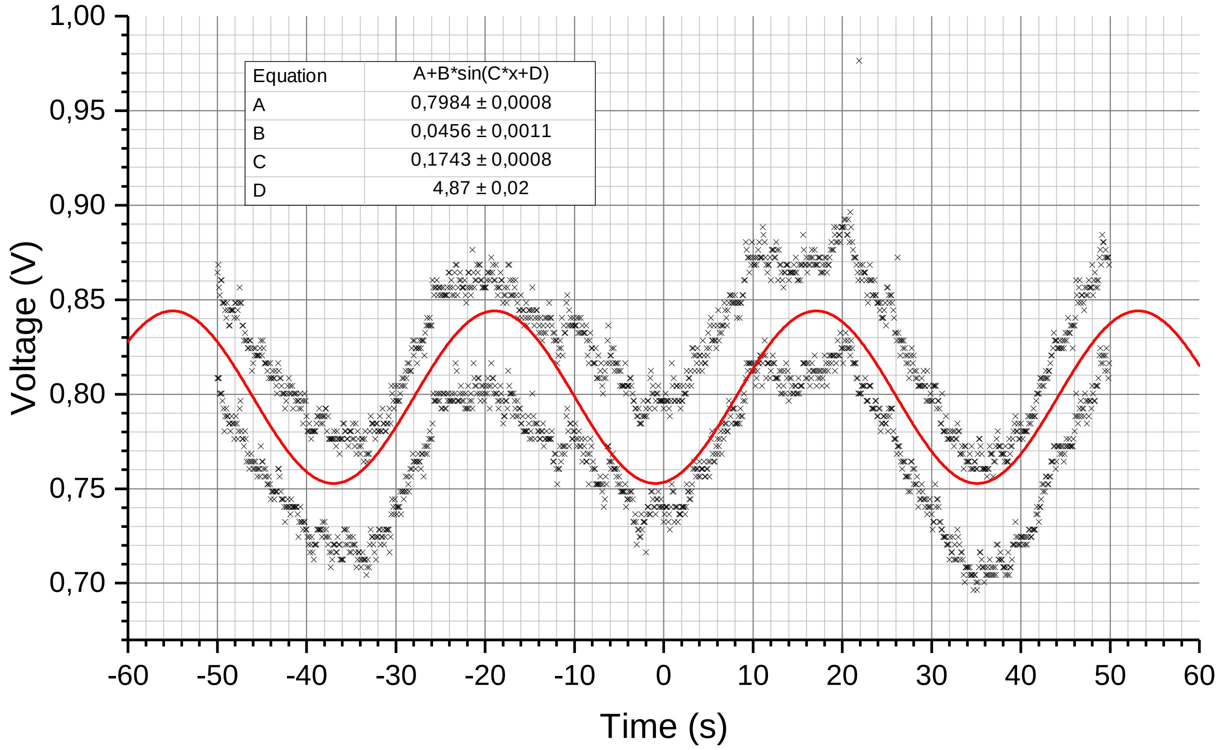


Figure 20: Resistance 4 with rotating setting $w = 2$ [1]

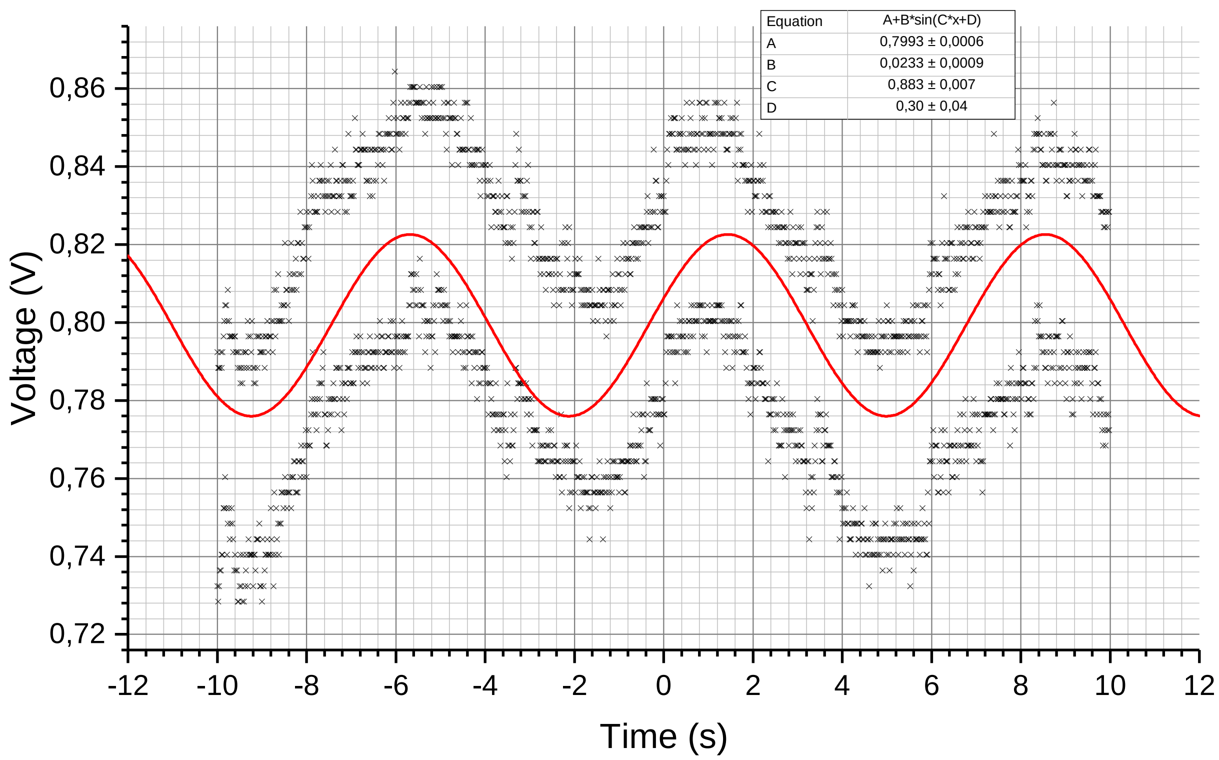


Figure 21: Resistance 5 with rotating setting $w = 10$ [1]

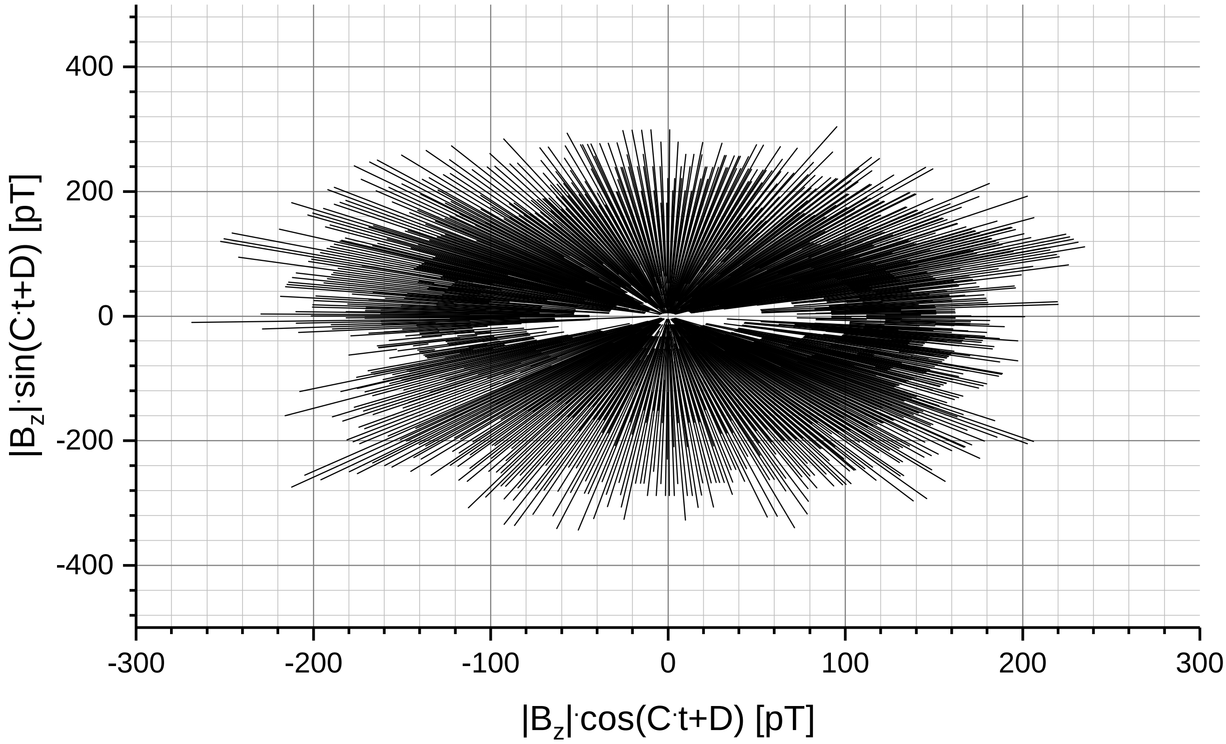


Figure 22: Resistance 5 with rotating setting $w = 10$ in polar form [1]

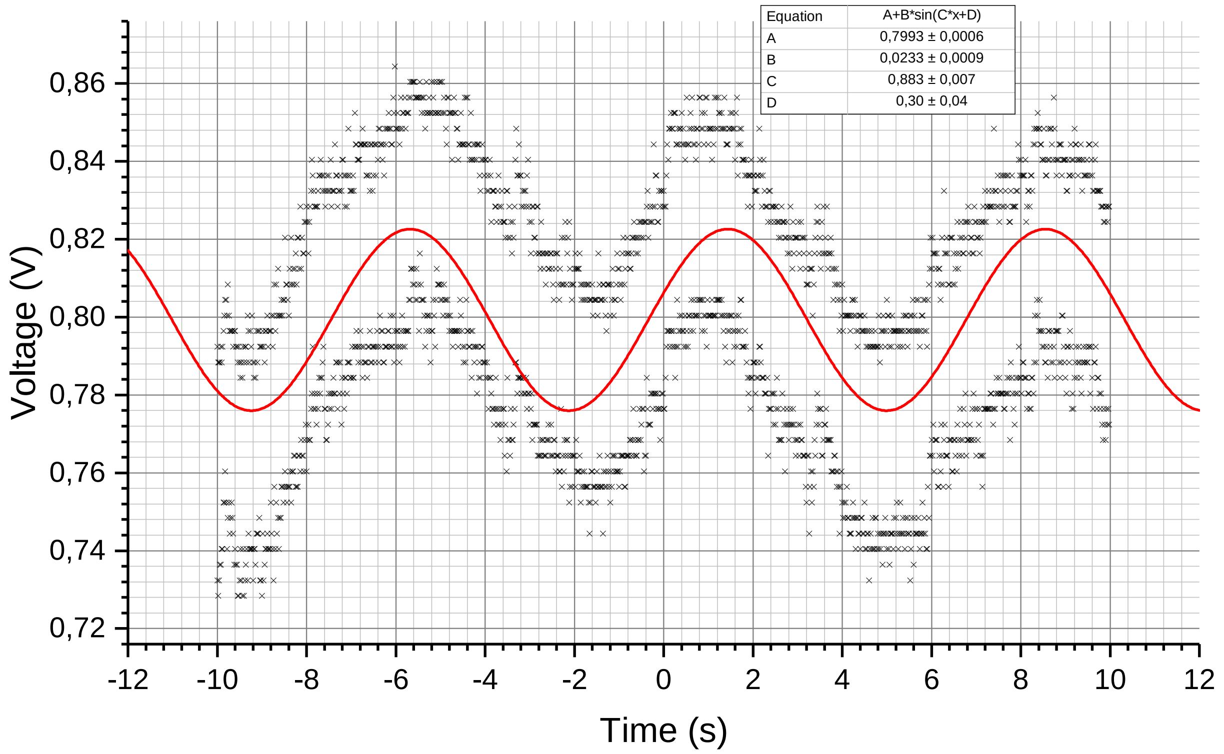


Figure 23: Resistance 5 with rotating setting $w = 10$ [1]

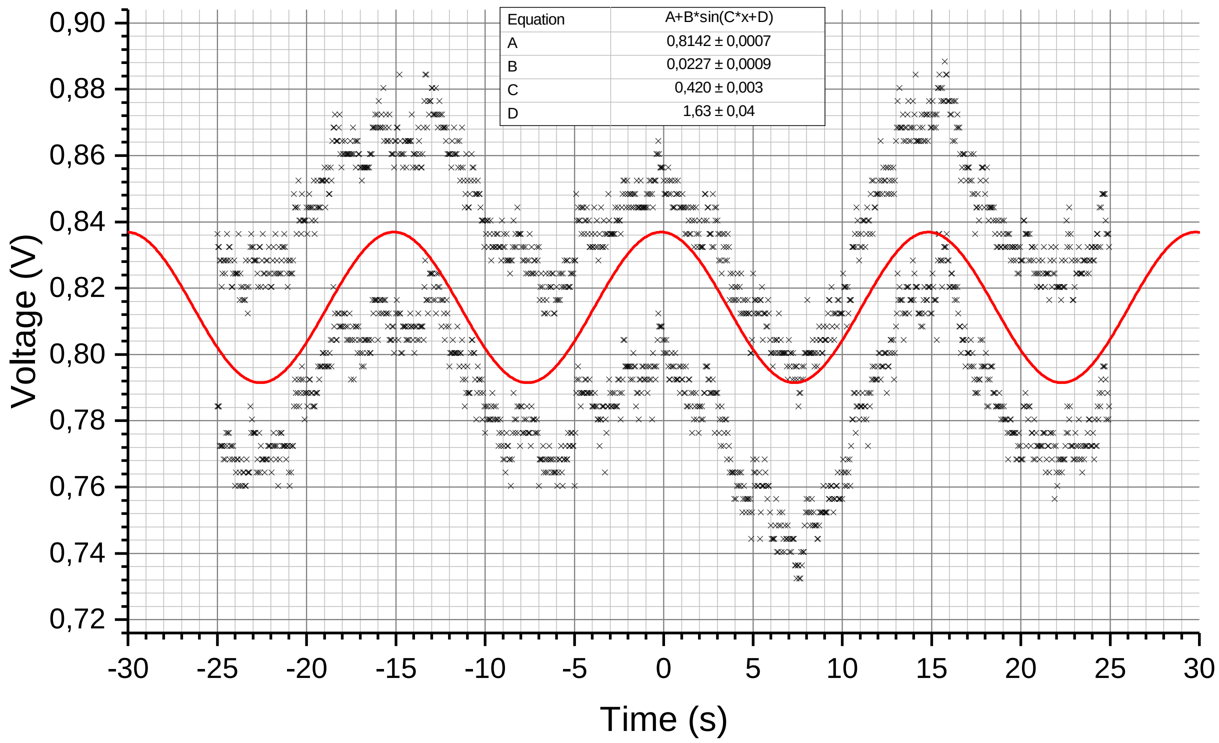


Figure 24: Resistance 5 with rotating setting $w = 5$ [1]

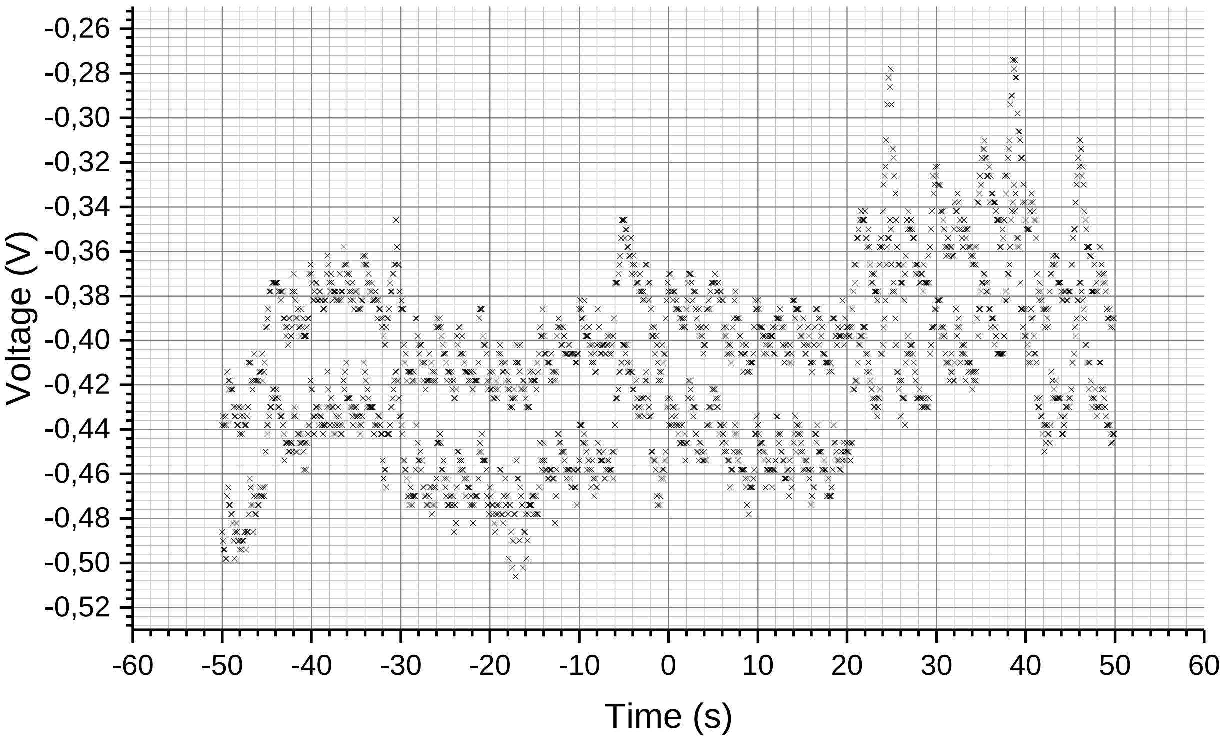


Figure 25: Resistance 5 with rotating setting $w = 2$ [1]

6.3 Diagrams of everyday objects

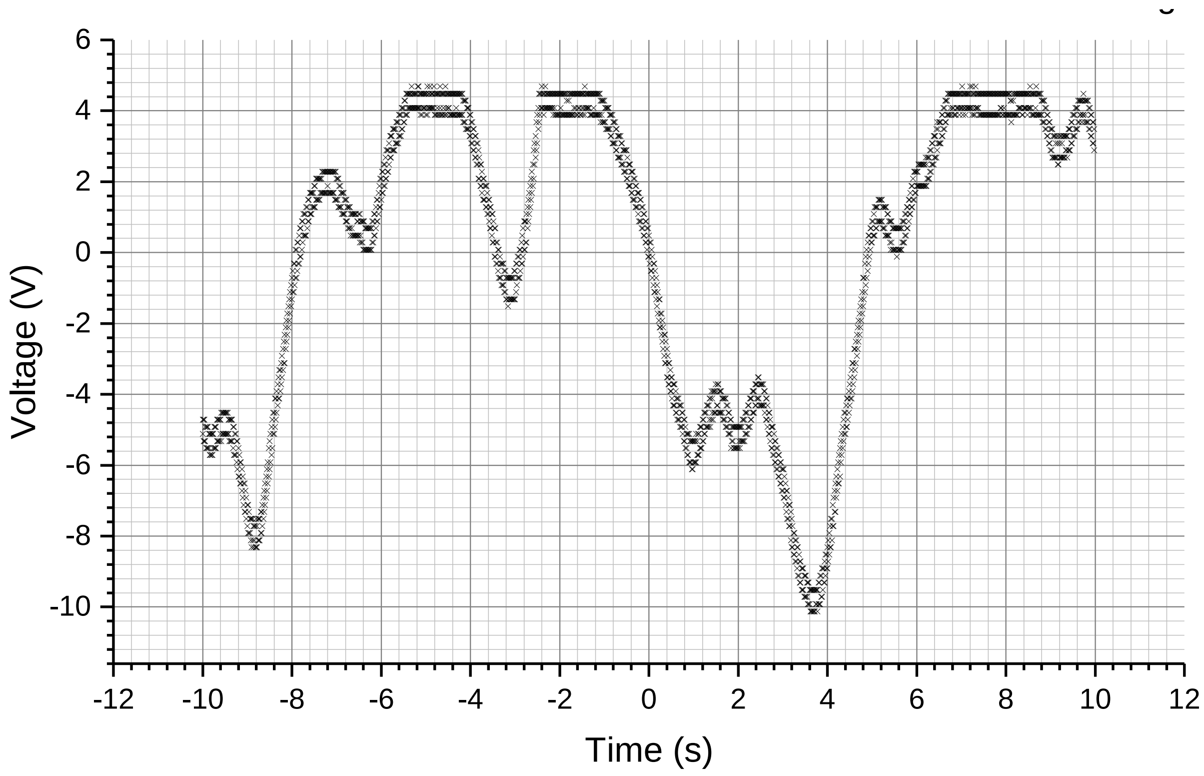


Figure 26: Crown cork with rotating setting $w = 10$ [1]

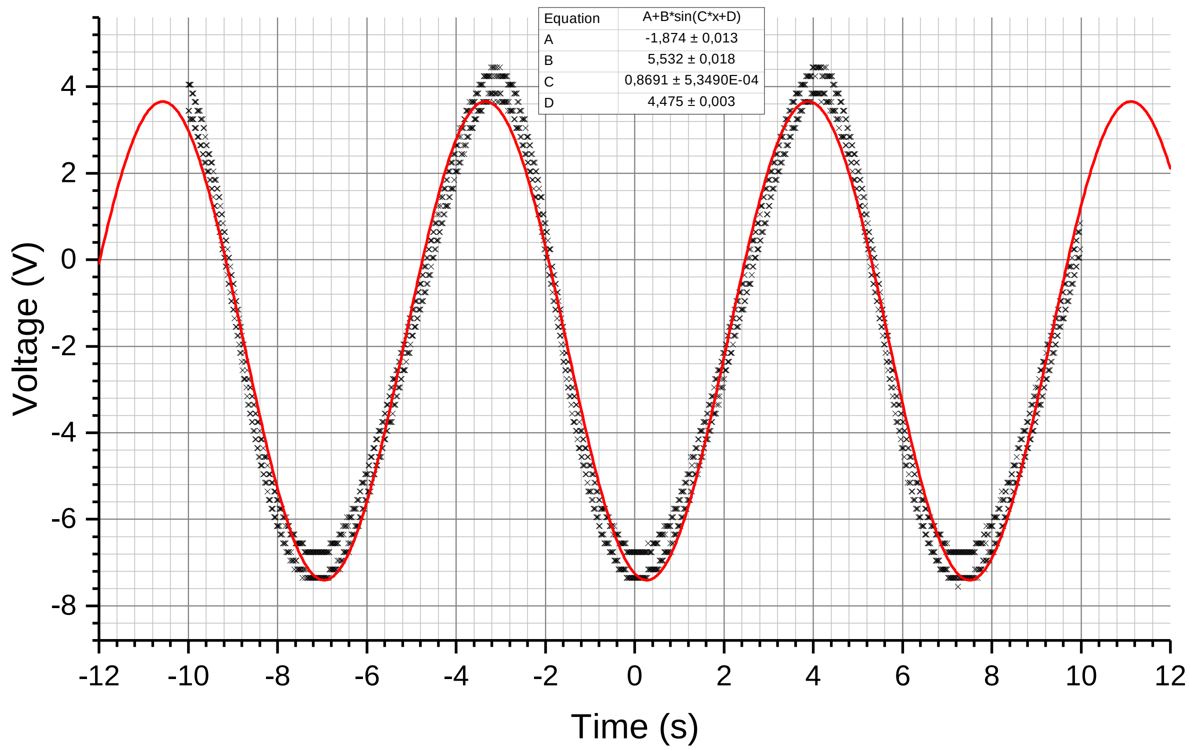


Figure 27: Magnetic flake with rotating setting $w = 10$ [1]

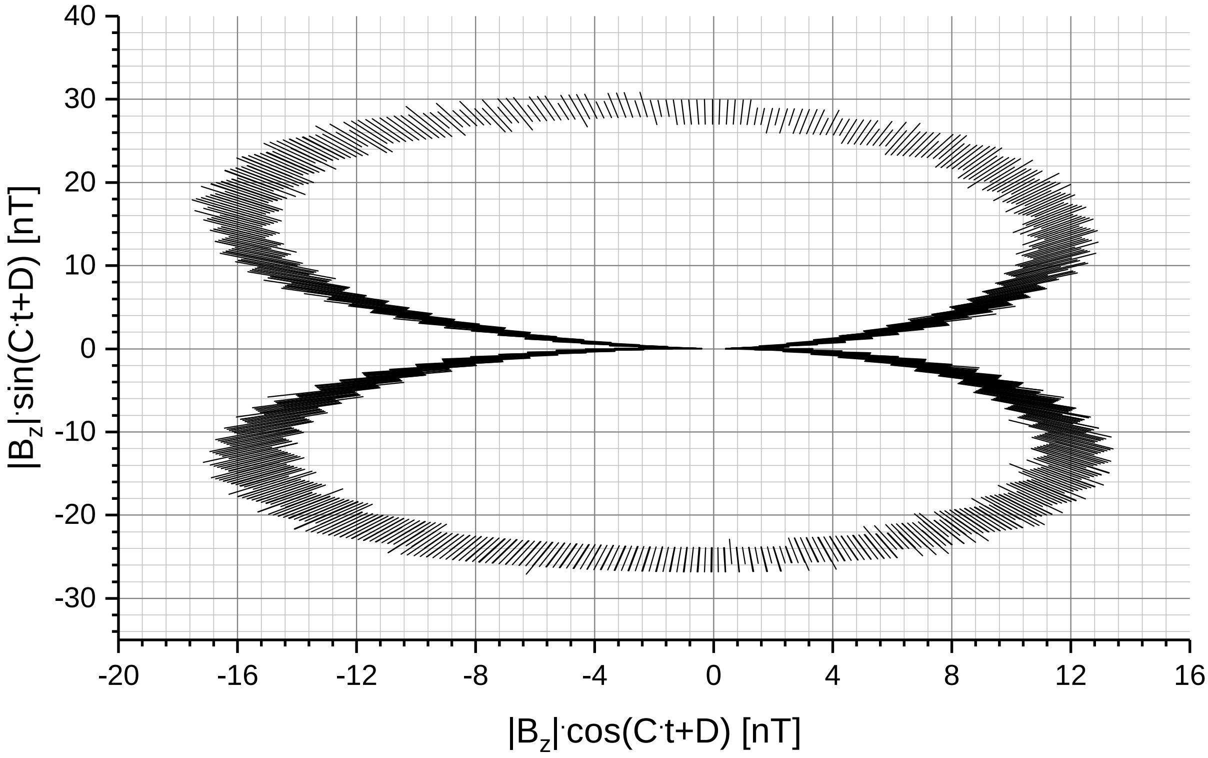


Figure 28: Magnetic flake with rotating setting $w = 10$ in polar form [1]

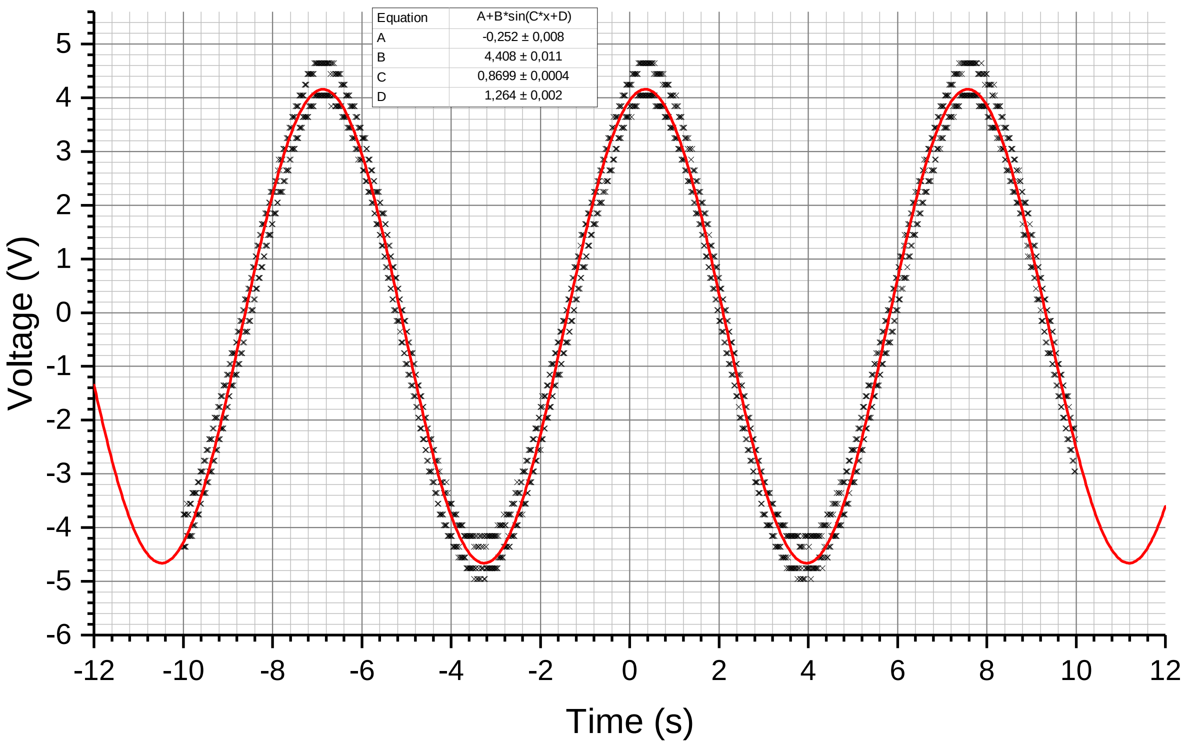


Figure 29: Metal stick with rotating setting $w = 10$ [1]

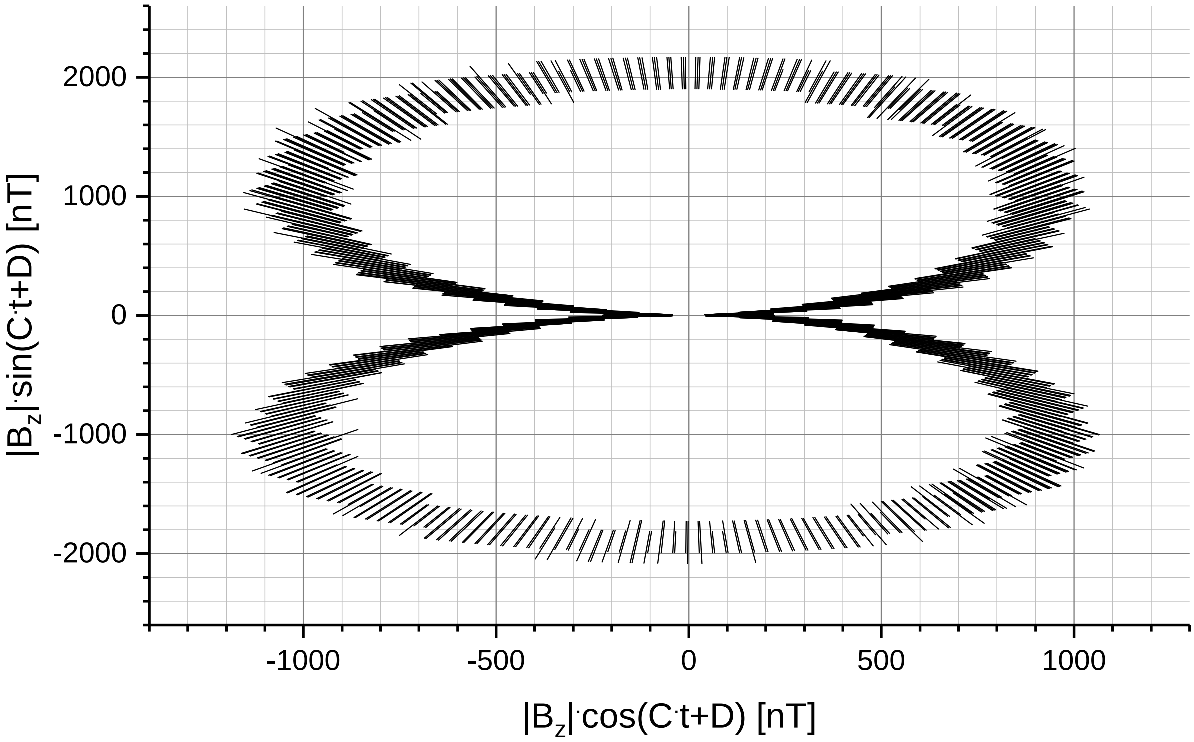


Figure 30: Metal stick with rotating setting $w = 10$ in polar form [1]

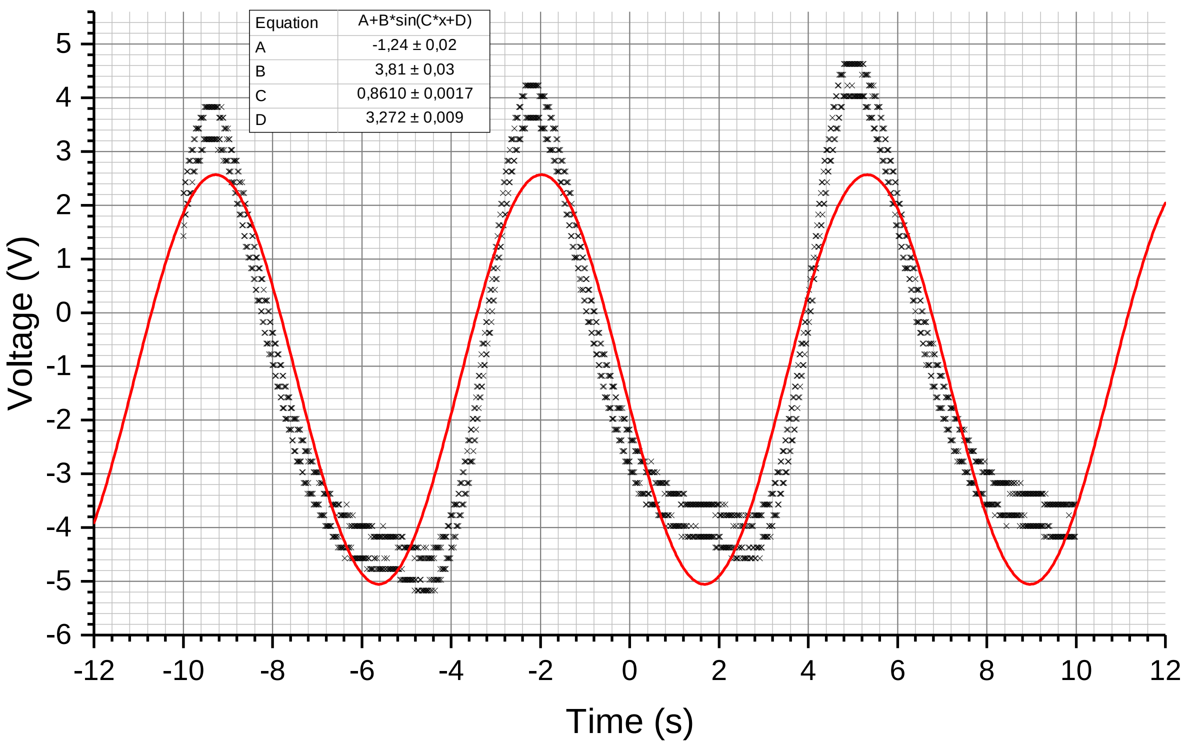


Figure 31: 2€ coin with rotating setting $w = 10$ [1]

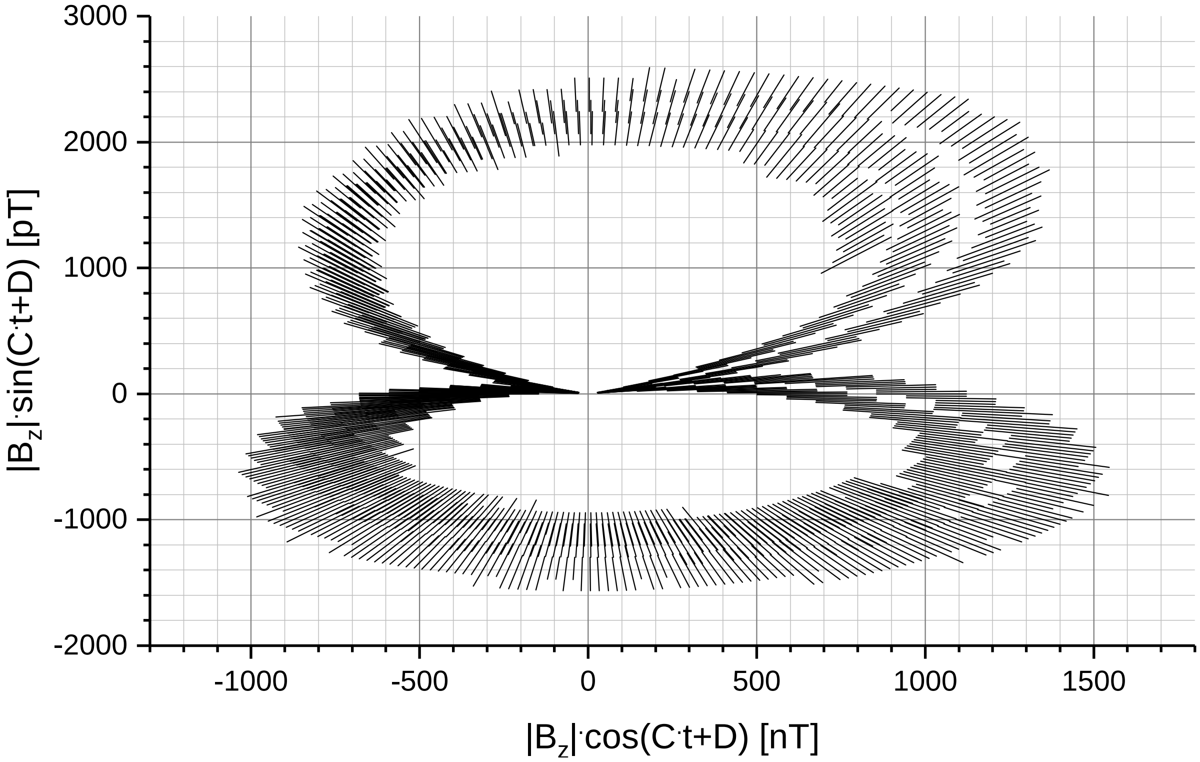


Figure 32: 2€ coin with rotating setting $w = 10$ in polar form [1]

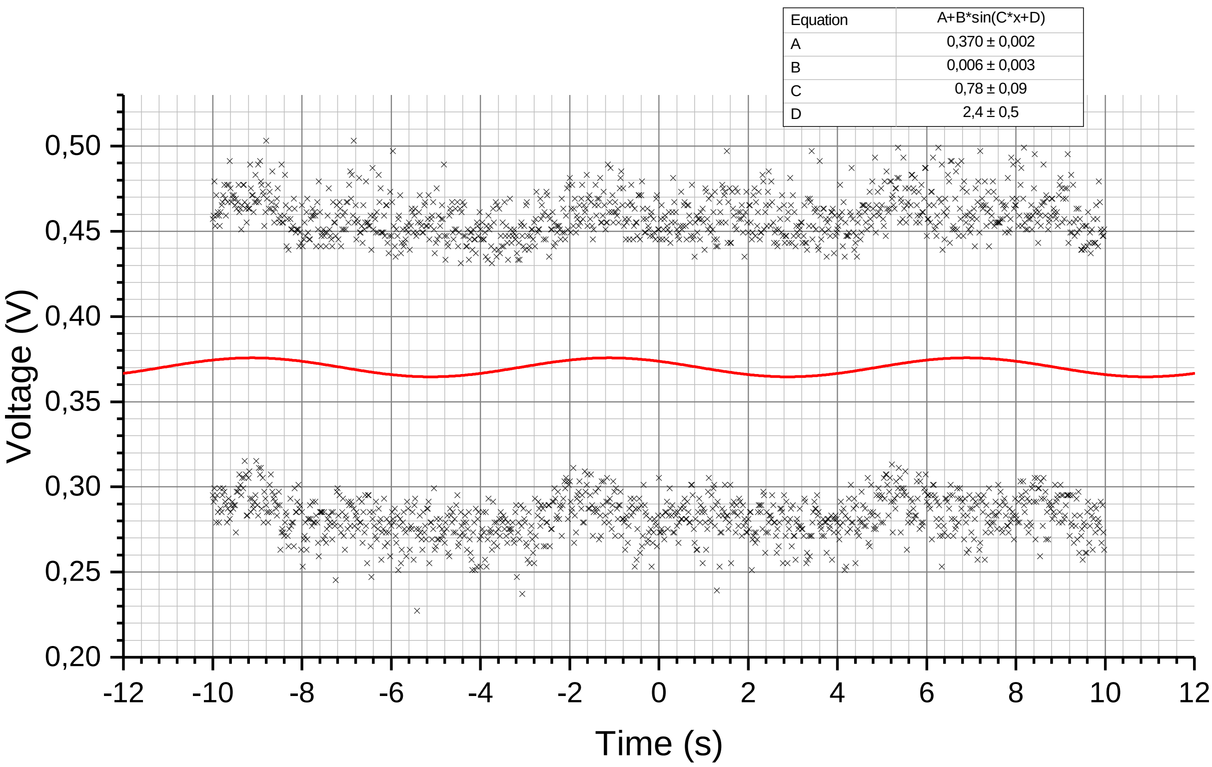


Figure 33: Empty aluminum holding with rotating setting $w = 10$ [1]

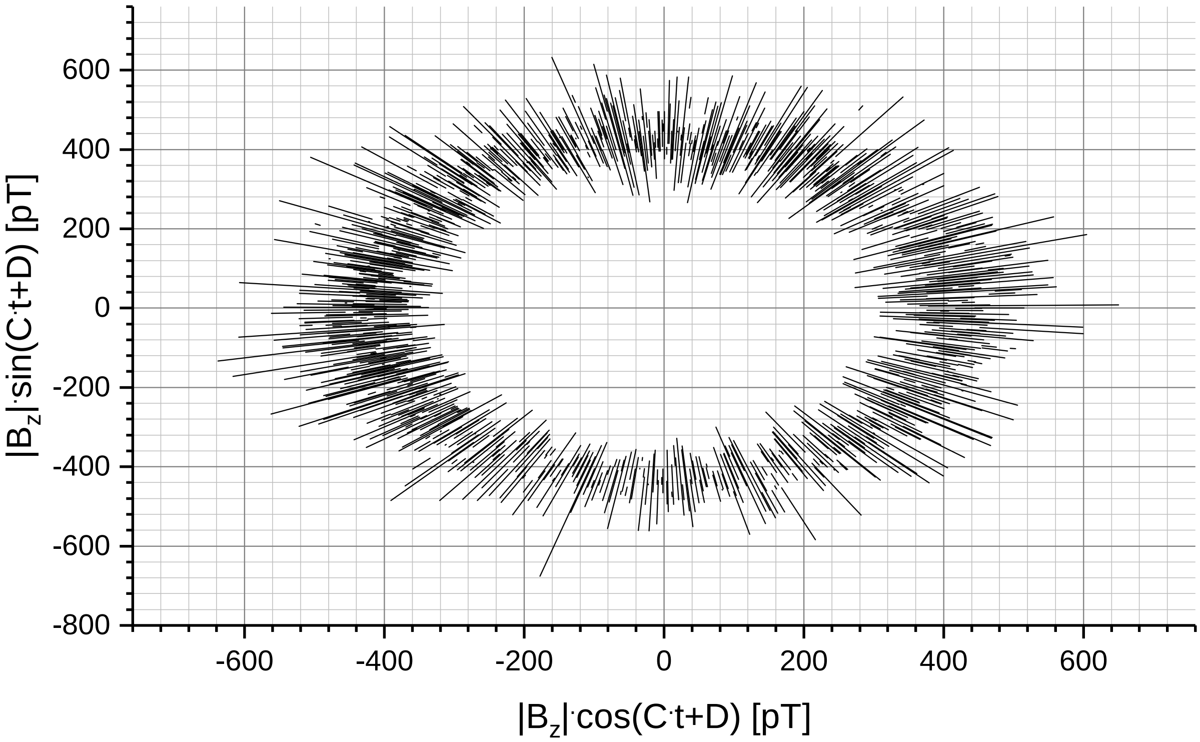


Figure 34: Empty aluminum holding with rotating setting $w = 10$ in polar form [1]

References

[1] The diagram was generated with OriginPro 2017G.

[2] Versuchsanleitung Fortgeschrittenen Praktikum Teil 1- SQUID

[3] Staatsexamensarbeit- Einrichtung des Versuchs "SQUID" - Volker Bange [http://hacol13.physik.uni-freiburg.de/fp/Versuche/FP1/FP1-11-SQUID/Staatsex-Squid.pdf] (called on 07.09.2017)
[http://hacol13.physik.uni-freiburg.de/fp/Versuche/FP1/FP1-11-SQUID/Anleitung.pdf] (called on 07.09.2017)

[4] Self-made with Microsoft Paint (Version 1703)