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Multi sequence hardware design for rotational drift spectroscopy

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Abstract

Rotational Drift Spectroscopy (RDS) is a novel spectroscopic method for magnetic nanoparticles. It is based on measuring the rotational drift of magnetic nanoparticle ensembles in liquid suspension in a rotating magnetic field, that is below the magnetic field strength necessary for rotating the magnetic nanoparticles synchronously. The resulting asynchronous rotational drift strongly depends on the properties of the magnetic nanoparticles and their environment. This allows for, e.g., detecting specific molecules via functionalized magnetic nanoparticles. The following work presents a compact rotational drift spectroscopy hardware design, which is controllable with python scripts and is especially designed for accommodating various kinds of RDS measurement sequences with differing hardware requirements.

I. Introduction

Rotational drift spectroscopy (RDS) [2, 3] aims at measuring the asynchronous rotation of magnetic particles in weak rotating magnetic fields. This phenomenon is demonstrated in [1] for a single functionalized microparticle, where it is used as a sensor allowing for the detection of single bacteria. In [1] the rotation of single micro particles is measured optically. RDS inductively measures the macroscopic magnetization of large ensembles of magnetic nanoparticles in liquid suspension. In general, the magnetic moments of the magnetic nanoparticles are oriented randomly, resulting in zero external net magnetization. Hence, the method requires an initial pulse for aligning all particles in one direction. This alignment decays due to thermal interaction and due to particle differences, which results in a distribution of rotational drift frequencies in a rotating magnetic field. This alignment before the measurement is a critical aspect of RDS. Three different ways for achieving this initial alignment are presented in [2, 4, 5]. In [2], a short magnetic field pulse is applied before starting the rotating magnetic field. This method has the disadvantage, that it generates strong disturbances in the same frequency range as the signal itself. In [4] orthogonal frequency mixing is suggested for achieving the initial alignment. It has only frequency components above the RDS signal bandwidth and therefore starting the sequence doesn't generate disturbances in the receiver low-pass filter. In [5] it is demonstrated, that applying a small static offset field achieves the necessary particle alignment under certain conditions. These three sequence types are of interest independently of their different hardware requirements, since they have different signal properties, potentially allowing for accessing different particle properties. E.g., while the method presented in [5] has the least hardware requirements, it doesn't allow running echo sequences like [2] and [4]. The following work presents a compact RDS scanner design able to accommodate those different sequence types.

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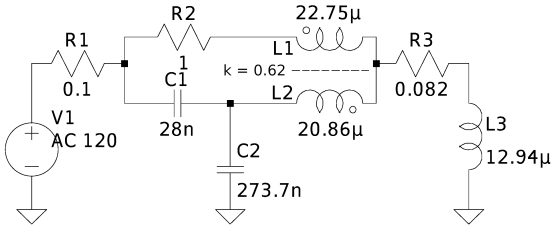

Figure 1: Impedance matching for the excitation coil in x-direction (L3). Besides the typical match-and-tune capacitors (C1 and C2) there is an additional branch with a decoupling transformer (L1 and L2, two air coils with a coupling factor k = L3 / L2), which allows static offset currents and low-frequency pulses in L3 while also being resonantly tuned to 50 kHz.

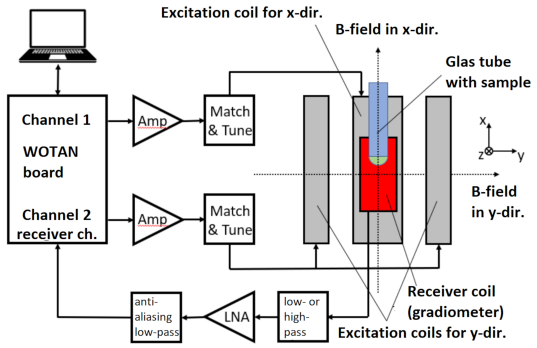

Figure 2: Schema of setup.

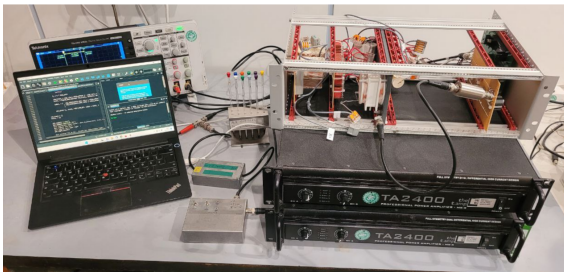

Figure 3: Spectrometer setup.

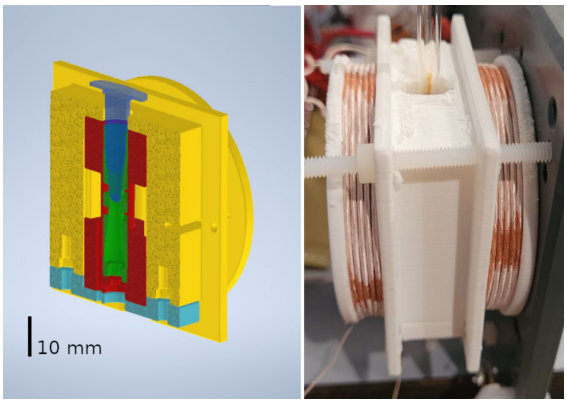

Figure 4: Spectrometer coil system. Left: 3D cut with the red part being the coil scaffold for the x-direction and the yellow part being the scaffold for the coils in y-direction. The photograph on the right shows the Helmholtz coil pair in y-direction.

II. Material and methods

The design mainly aims at accommodating the following three different sequence types:

1. MPS (Magnetic Particle Spectroscopy) with static offset fields
2. RDS with static offset fields
3. RDS with unipolar magnetic pulses

The first one comes for free because it is a subset of RDS with static offset fields, which consists of orthogonally orientated excitation coils for generating a rotating magnetic field. The working frequency was chosen to be 50 kHz with resonant excitation coils for the x- and y-direction. The coil for the x-direction can also generate static offset fields and magnetic pulses with frequencies way below 50 kHz.

The circuit in fig. 1 shows how to resonantly tune the excitation coil to 50 kHz while also allowing static- and low-frequency currents. The audio amplifier provides more maximum voltage swing than necessary for generating 50 mT in x-direction, which is the maximum excitation field strength aimed at. This allows working with frequencies that are some 100 Hz below or above the resonance frequency.

Fig. 2 shows the schema of the spectroscopy design. The sequences for the x- and y-coils are generated with two on-chip 8 bit DACs (250 kS/s) of the mixed signal chip CY8C5888LTI-LP097 (Infineon, Neubiberg, Germany) of the WOTAN board [6]. The signal acquisition is done with two on-chip 12 bit ADCs (2x 1 MS/s). The sequences and the data acquisition are controlled with python scripts. The WOTAN board is connected with USB to a laptop. PCB Layout of the WOTAN board, firmware and python code is provided in [7].

The complete setup is shown in fig. 3. The x- and y-coils where each driven with a TA2400 audio amplifier (Thomann, Treppendorf, Germany). The 19" rack contains the impedance matching for the coil system, the coil system, the receive chain filter (switchable between low-pass filter for RDS sequences (8-pol. Bessel-filter with f_0=10 kHz) and high-pass filter (6-pol. Chebychev-filter with f_0=92 kHz) for both RDS and MPS sequences) and the WOTAN board. The coil system could generate magnetic fields up to 50 mT at 50 kHz.

The coil system is shown in fig. 4. The coil for the x-direction is a solenoid. The excitation field in y-direction is generated with a Helmholtz coil pair. The receiver coil is realized as a tunable gradiometer inside the red scaffold in fig. 4. The coil system was designed for 5 mm glass tubes.

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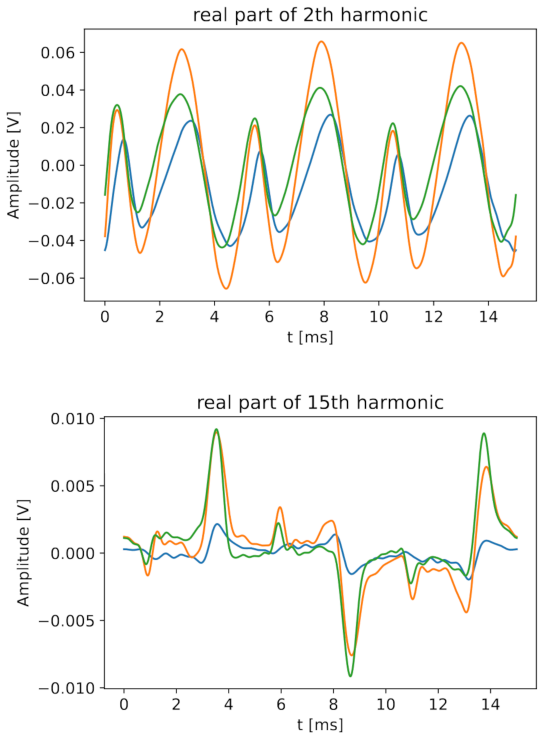

Figure 5: Real part of the 2^{nd} and 15^{th} harmonic of the signal for different particles. The particles used are from Ocean NanoTech (San Diego, USA). The original concentration was used in all cases (5 mg/ml). Particles: SHP30 (blue), SPA25 (green) and SPA20 (orange) with the rotating magnetic field strength B_{rot} = 30 mT.

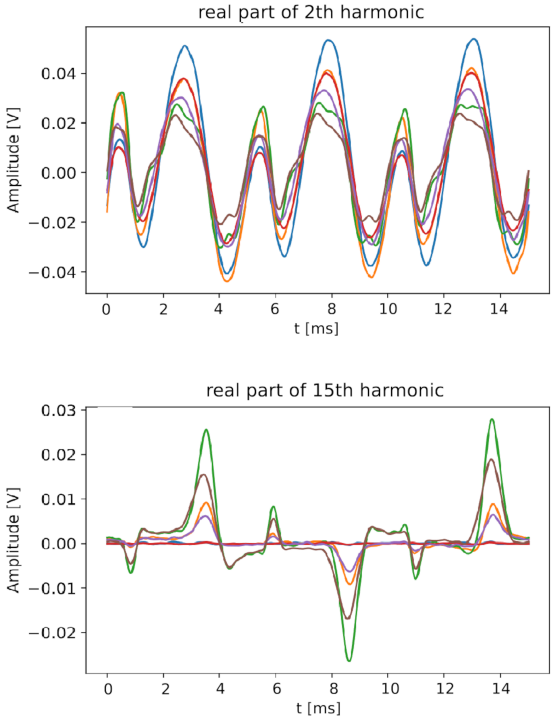

Figure 6: SPA25 particles (same as in fig. 5, undiluted, i.e., 5 mg/ml) for different amplitudes with and without glycerol. Blue: B_{rot} = 10 mT; Red: B_{rot} = 10 mT + glycerol; Orange: B_{rot} = 30 mT; Pink: B_{rot} = 30 mT + gly.; green: B_{rot} = 50 mT; Brown: B_{rot} 50 mT + gly. The glycerol content was about 2/3 versus 1/3 of undiluted particle suspension.

The time evolution of the 2^{nd} and 15^{th} harmonics in fig. 5 and fig. 6 is extracted by shifting the Fourier transform of the complete 15 ms signal by $f_{shift} = n\,(f_x + f_y)/2$ toward f=0 Hz, where n is the order of the harmonic, f_x and f_y the frequency of the x- and y-channel, the values above 2.5 kHz are set to zero and the remaining data is transformed back to the time domain and multiplied by 2 to get the correct amplitude.

III. Results

Fig. 5 and 6 shows data acquired with the spectroscope.

The sequence duration is 15 ms. The frequency in x-direction is 50.0 kHz, the frequency in y-direction is 50.2 kHz. This results in a rotating field that periodically changes its direction six times in 15 ms, i.e., the rotating field continually changes its ellipticity.

The frequency difference of 200 Hz results in a signal periodicity of 5 ms. The described way of extracting the time evolution of the harmonics assumes the signal in x- and y-direction being equally weighed while the receiver coil is only sensitive in x-direction. This leads to an apparent periodicity of 10 ms. The rotating magnetic field changes its rotating direction every 2.5 ms and should produce a mirror signal every 2.5 ms. The magnetic field amplitude is different in these two 2.5 ms intervals due to coupling between the x- and y-coil, which is why this signal mirroring is not observed.

The time evolution of the 2^{nd} and 15^{th} harmonic in fig. 5 is shown for three different particle types. SHP30 is expected to show mainly Brownian rotation as compared to SPA20 and SPA25. It is therefore expected to show a lower signal strength for higher harmonics due to less rotational mobility. In fig. 6 the signal dependency is evaluated for two different viscosities and different excitation field amplitudes. The latter mostly affects only the overall signal strength. As expected, the 15^{th} harmonic decreases significantly when glycerol is added. What can also be noted, is that some signal features remain unaffected. This means that changes in viscosity change the shape and not just the amplitude of the signal. This dependency can be rather complicated if aggregates of magnetic particles are considered. In case of single core particles as investigated here, the Langevin equation in [3] can reproduce the basic structure of the signal and its dependency with respect to rotational mobility.

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Table 1: Transmit coils for the X- and Y-direction (Tx-X and Tx-Y) are made of litz wire with 90 strands of 0.1 mm), receive coil is made of litz wire with 12 strands of 40 µm and is oriented in X-direction.

Coil	Diameter	Windings	Resistance	Inductance
Tx - X	10 mm	36	0.070 Ω	12.9 µH
Tx - Y	45 mm	25	0.25 Ω	120 µH
Rx - X	5 mm	2x 30	3.5 Ω	12.0 µH

IV. Conclusion

A compact RDS spectrometer for multiparametric sequences was designed around the WOTAN board, fully controllable with python scripts. The spectrometer allows a variety of RDS sequences that differ with respect of sensitivity to different particle suspension properties. This opens new possibilities with regard of bioassays, particle characterization and highly specific fingerprinting.

Acknowledgments

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Author's statement

Conflict of interest: Authors state no conflict of interest.

References

[1] McNaughton et. al, „Single bacterial cell detection with nonlinear rotational frequency shifts of driven magnetic microspheres“, Applied physics letters, 2007.

[2] Rückert et. al., "Rotating Drift Spectroscopy for Magnetic Particle Ensembles", IEEE Proc. on IWMPI Berlin, 2014.

[3] Rückert et. al., "Simulating the Signal Generation of Rotating Drift Spectroscopy", IEEE Proc. on IWMPI Berlin, 2014.

[4] Rückert et. al., "Zero dead time rotational drift spectroscopy for magnetic particle imaging", IWMPI Istanbul, 2015.

[5] Rückert et. al., "RDS: Measuring Fast Relaxating Magnetic Nanoparticle Ensembles", IWMPI Lübeck, 2016.

[6] Rückert et. al., "loW cOst ulTra small formfactor console for MPI", IWMPI Hamburg, 2018.

[7] https://github.com/mnruecke/RDS_WOTAN.

